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Additive Manufacturing

SLM of Aluminium and Titanium Alloys - Some lessons learned

Presented by:
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- Nottingham Background
- Lattice Design
- Investigating Density
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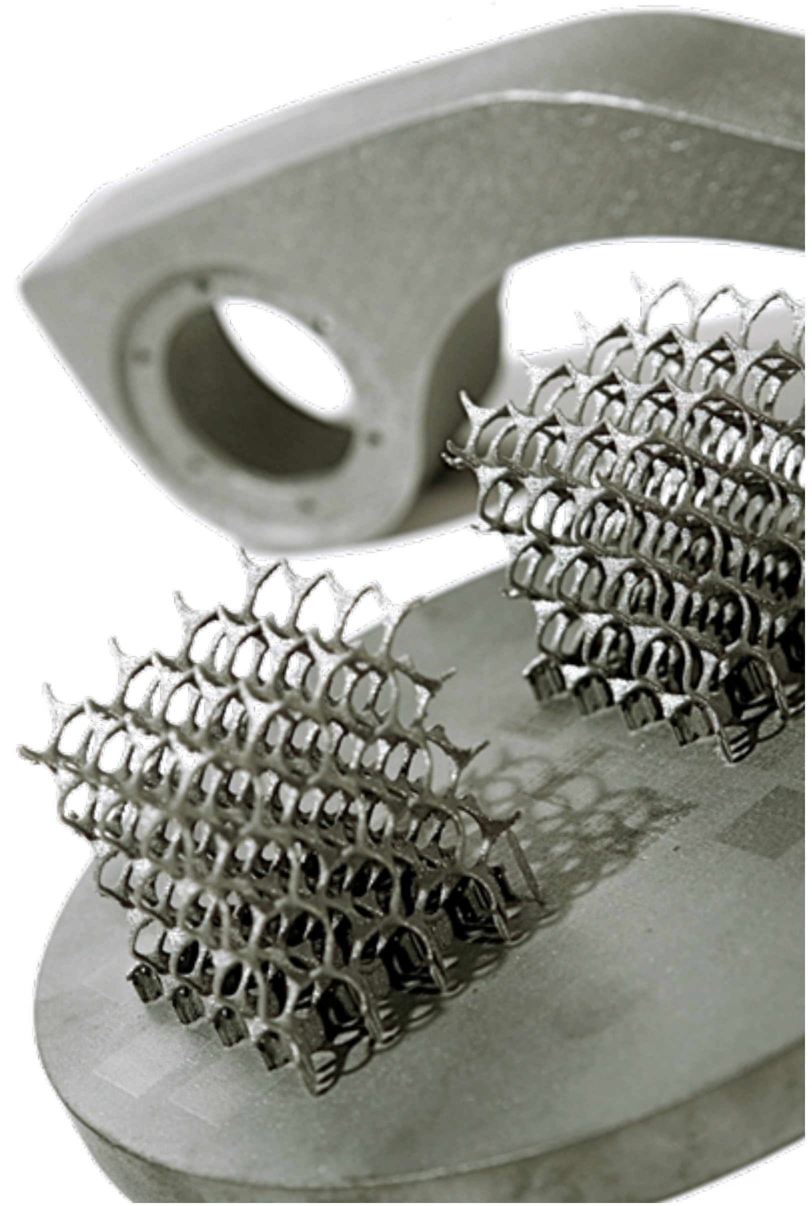
- Bringing it all together



3DPRG Staff

EPSRC Centre for
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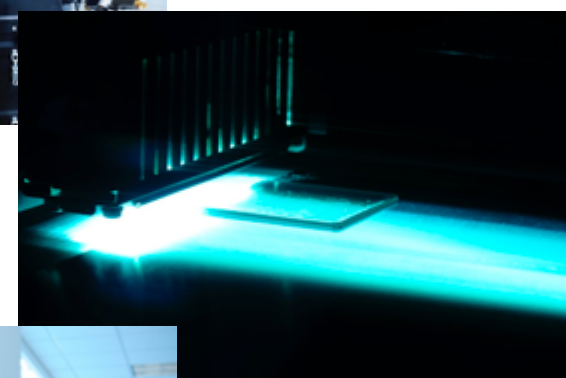
Additive Manufacturing

- **Group established in 1992 on RP and RT**
  - Began AM research in 2000
  - Began Multifunctional AM in 2011
- **Over 70 staff and Post-Grads dedicated to AM**
  - Currently have vacancies for Post-Doc and Research Students (15 per year)
  - Oct'16 over 90
- **Host 2 EPSRC Centres:**
  - Innovative Manufacturing in AM
  - Doctoral Training in AM (66 studentships)
  - Funding (last 3 years) - $35M
- **Spin Out Company**
  - Added Scientific Ltd



Sciences

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General 3DPRG AM Equipment

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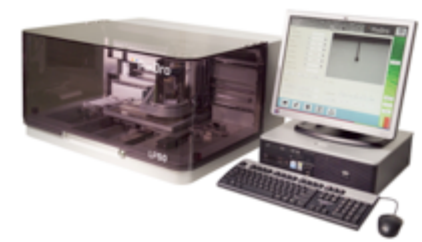
Metallic Powder

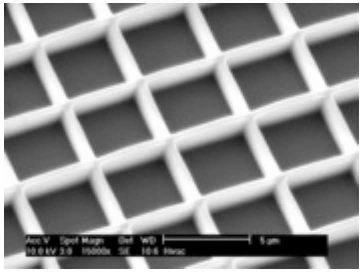
Polymer Powder

Polymer Jetting



Polymer Filament

Nano-scale



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New Equipment

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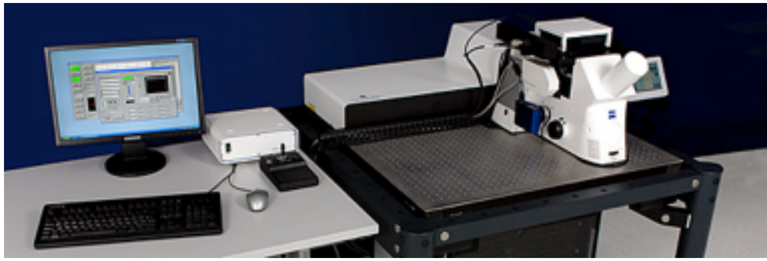
- JetX Multi-Material (6) Printer, 250x250x200mm envelope

- Nanoscribe Professional GT, <200nm feature resolution, up to 100x100mm envelope



- MetalJet Multimaterial High Temperature 4-Head System

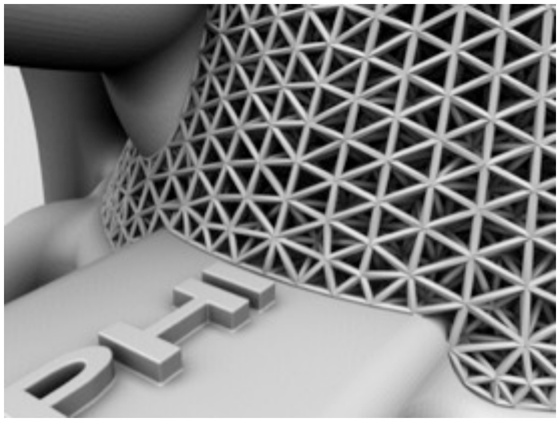
Rationale of the Presentation

- Acceptance of SLM depends on the material quality of the printed parts and repeatability of the process
- Over the last 10 years, great research efforts have been devoted to reduce porosity and establish the relationship between process – microstructure – mechanical performance of the printed parts
- It is now clear that the success of SLM relies on the comprehension of the events that take place at a microscopic scale during the melting and the solidification of the powder bed
- We need to use this information to inform and develop material models that can inform the process beforehand

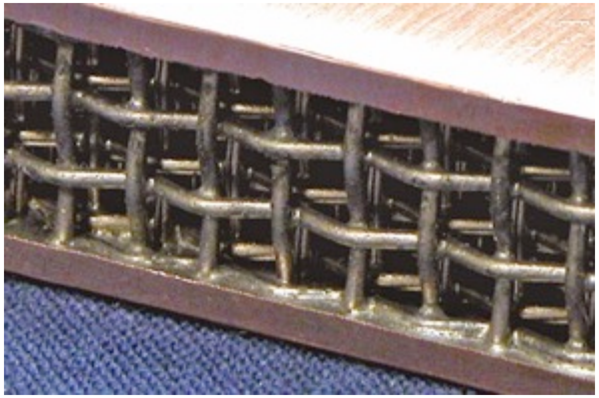
Lattice Design & Optimization

Lattice structures

Energy absorption

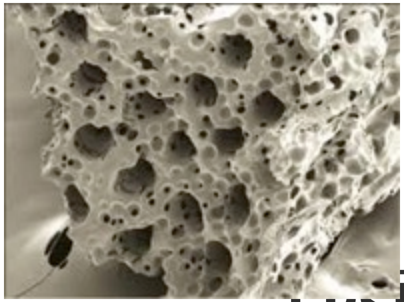


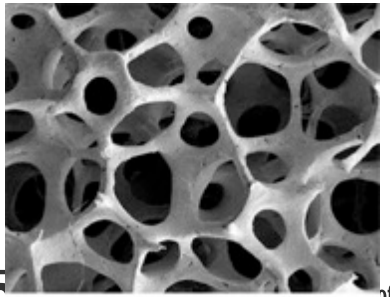
Thermal Dissipation



Lightweight design: Spinal Implant

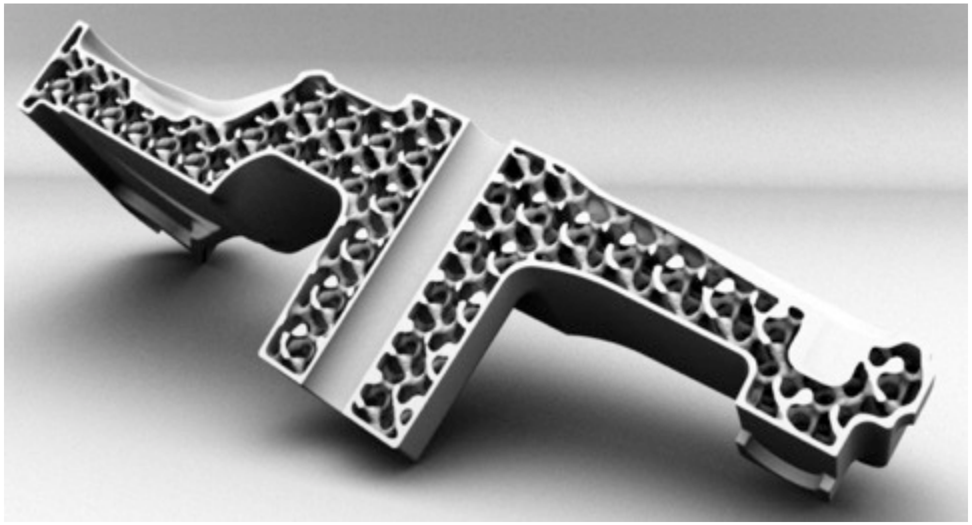
- Large surface area may also be beneficial, e.g. bonding, catalysis

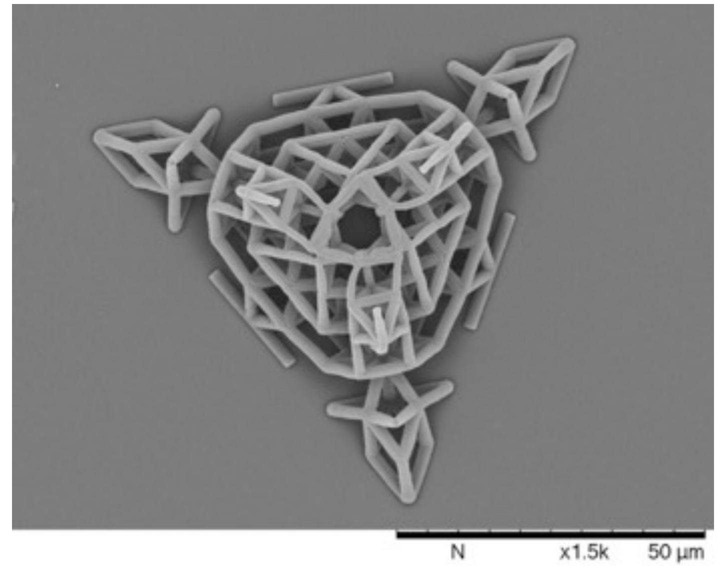


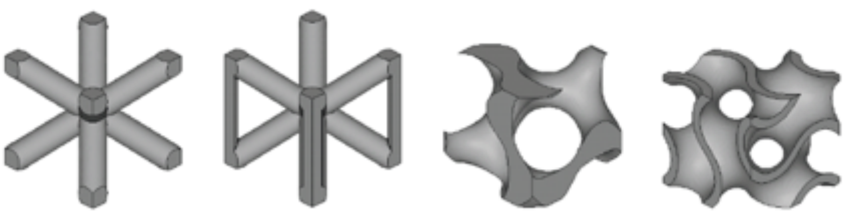


Lattice Structures

- **Structures filled with repeating units (or cells)**







FEA Evaluation

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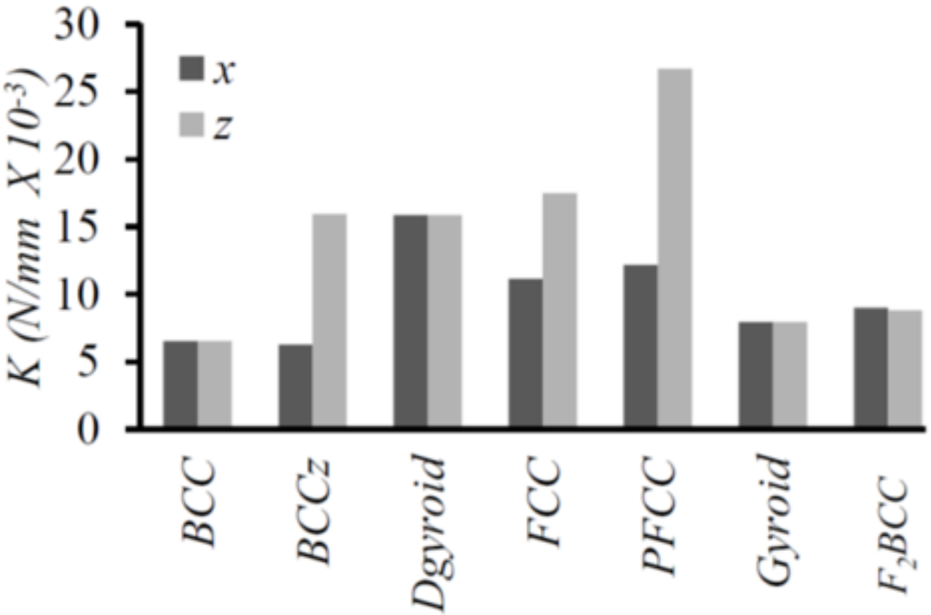
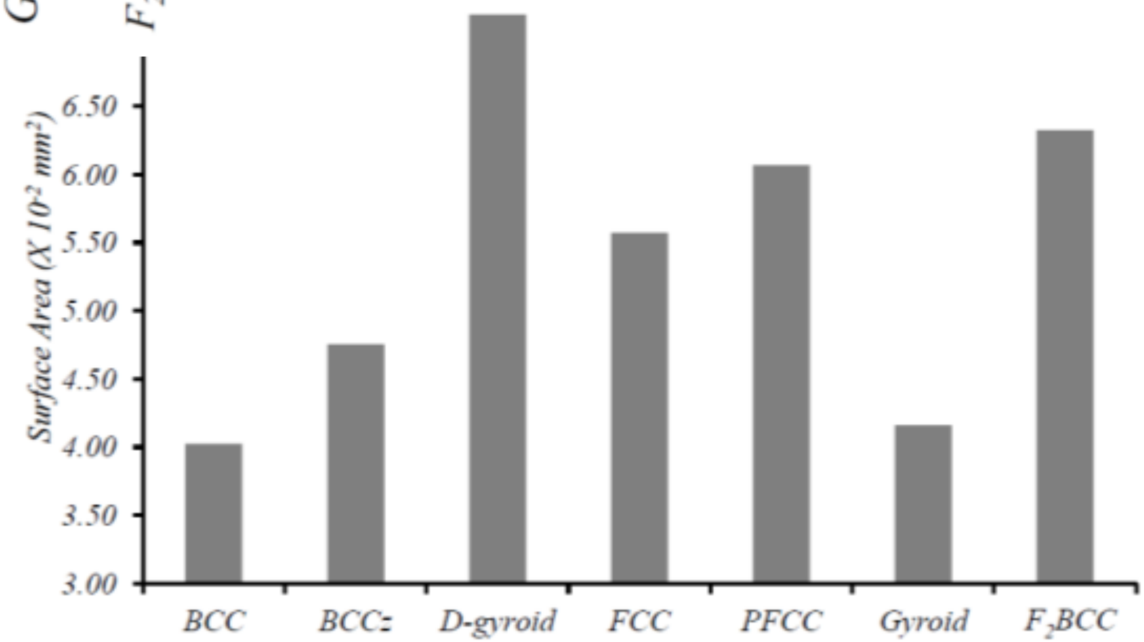


Mechanical properties:

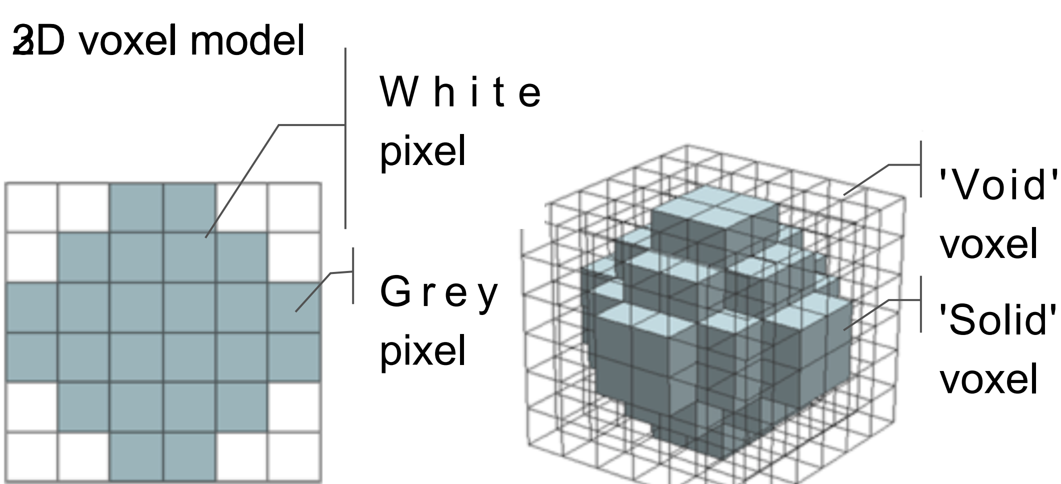
- Stiffness
- Maximum stress
- Anisotropy

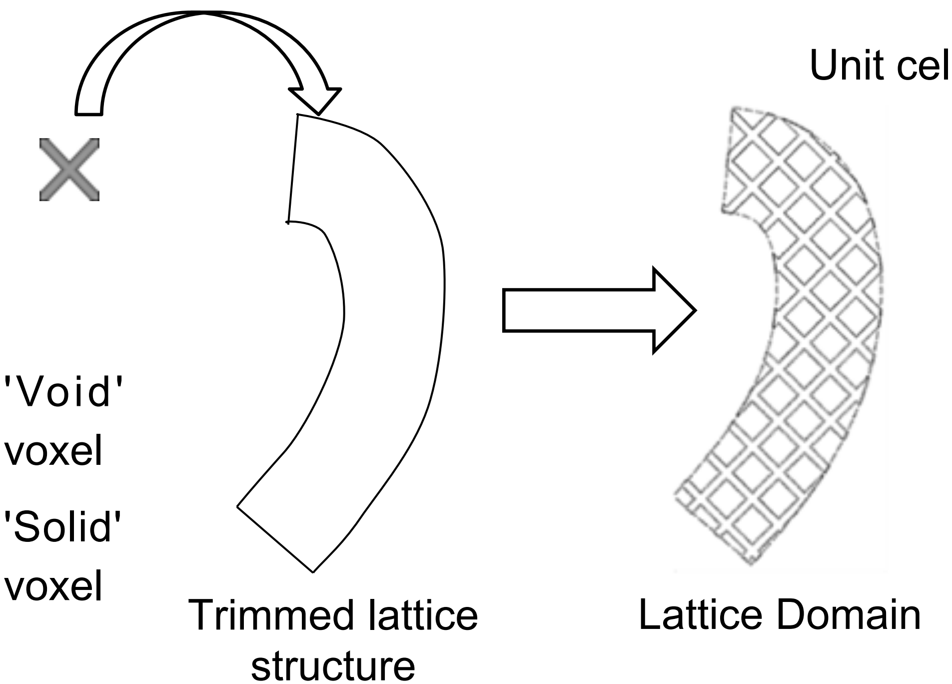
Surface area – radiative and convective heat transfer



Voxel based lattice method

- Voxel models:
  - More versatile than boundary representation models for lattice generation
  - Synergistic with voxel based manufacturing methods
  - Offer a way to construct high quality finite element meshes
  - Can be used to write machine files directly
  - Simple to add multi-material and multi-functionality
  - Simple to assign functionality to voxels
  - Internal complexity not memory dependent
  - Can be memory intensive
  - Not good for complex surfaces





Lattices: Advances

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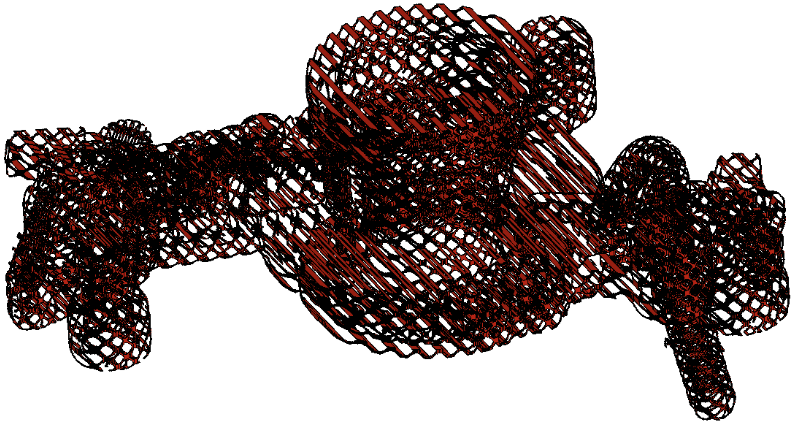
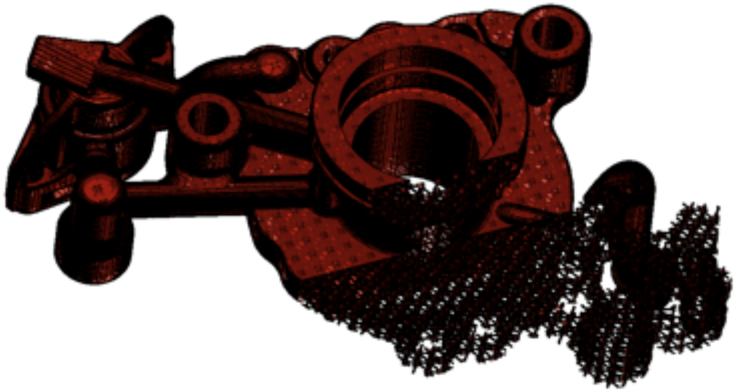
Original design

Unit Cell



Net Skin



Solid Skin on Lattice Structure

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Cellular structures with variable cell size

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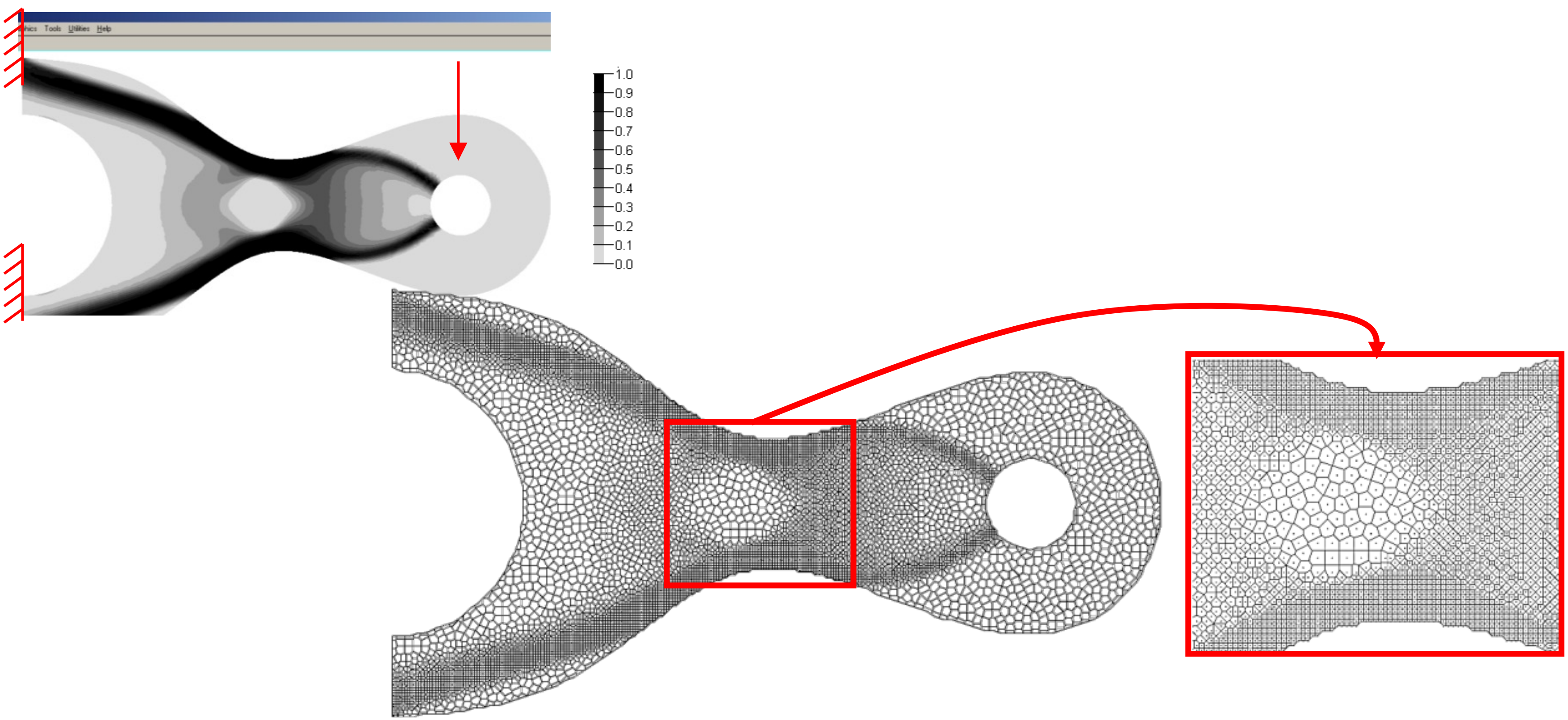
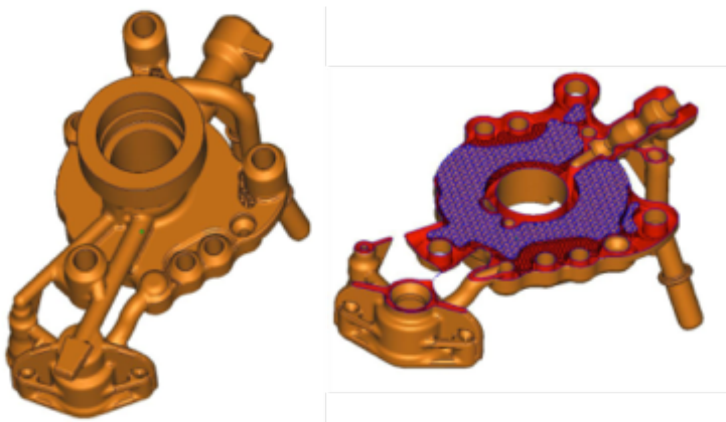
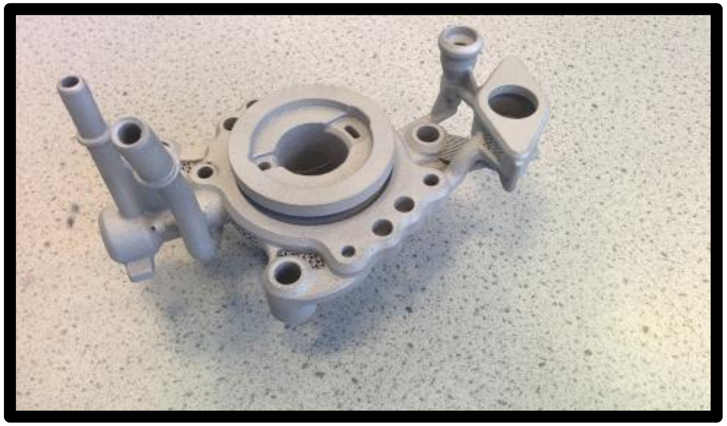
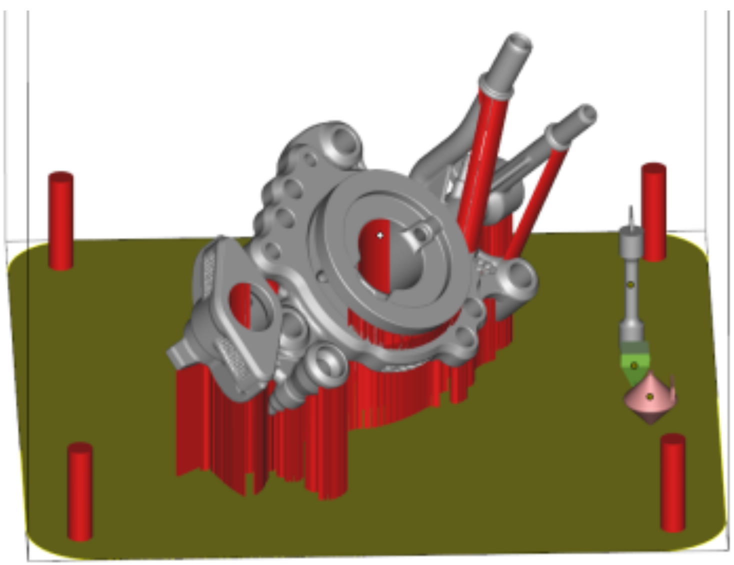
- **Dithering based method**
  - Used to design functionally graded lattices where the size of the cells can be varied.
  - Definition of functional grading
  - Error diffusion to generate dithered points of boundary and area
  - Application of connection scheme to generate structure cells

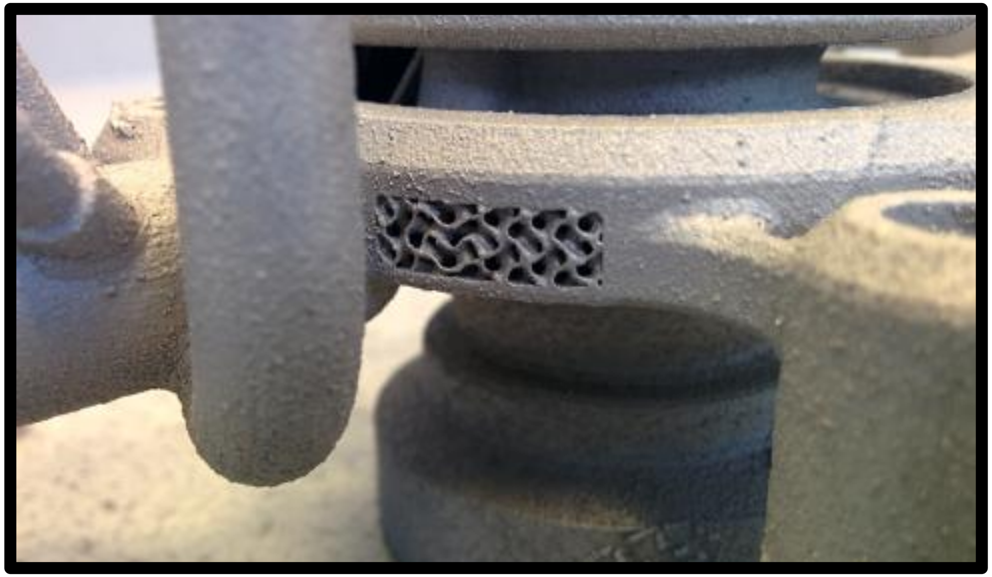


- Modified Delphi pump plate with latticed regions
- Supported and sliced by Renishaw









µCT Investigations

Materials - Aluminium

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- Aimed to use industrially relevant Aluminium alloys

- Interest in casting and higher performance grades
  - Initial work on 356, 6061
  - Initial work on 6061 showed high degrees of hot cracking during SLM and so it was decided to concentrate on 356 (AlSi10Mg)

6061 image large keyhole pores and hot cracking

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Density measurements

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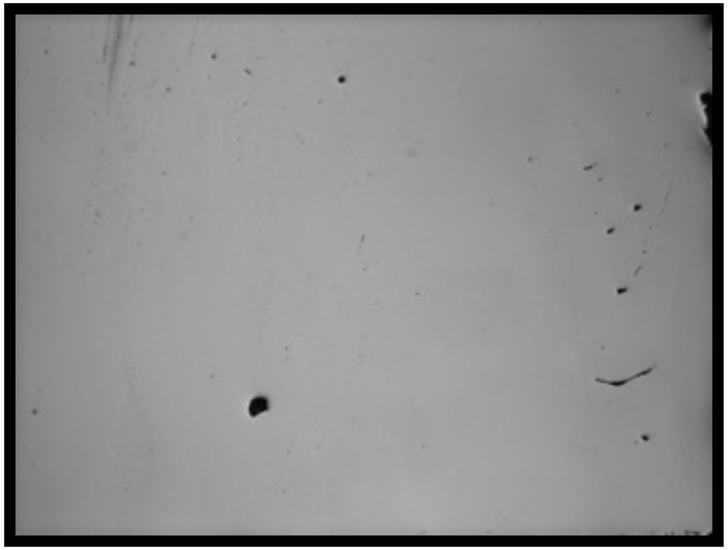
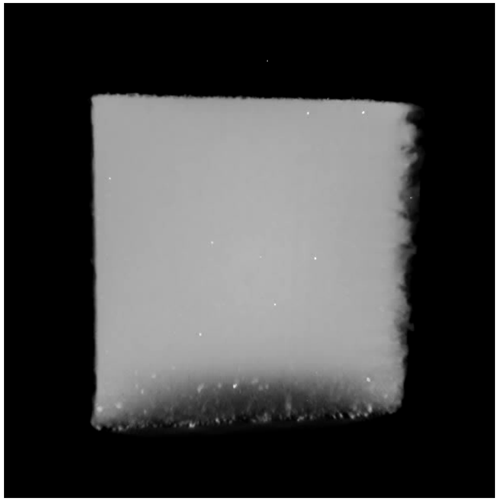
Optical microscopy



Standard approach ✓
Easy ✓
Cheap ✓

Only an areal density ✗
Aluminium 'smearing' ✗

X-ray computed tomography (CT)



More information ✓
Volumetric density ✓

More costly ✗

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The power of CT

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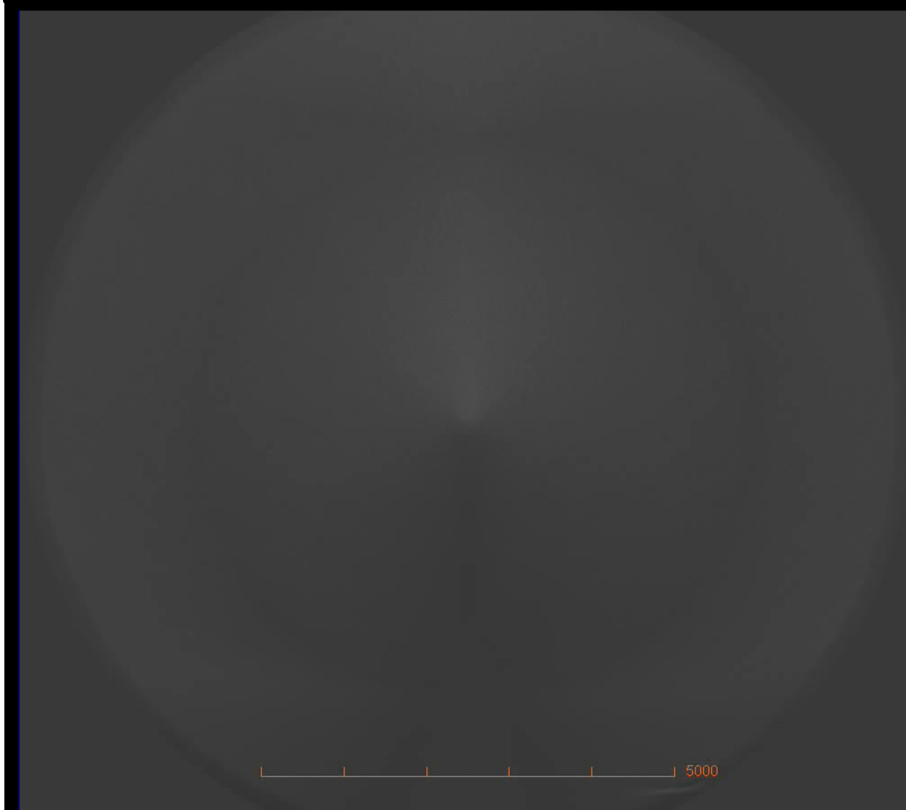
CT = 1000's of cross-sections



Initial test: 5 µm slices, ~ 5.5 µm res.

Density = 99.9%

(more representative than physical cross-sectioning)

Pore distribution

(aids scanning strategy development)

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The power of CT

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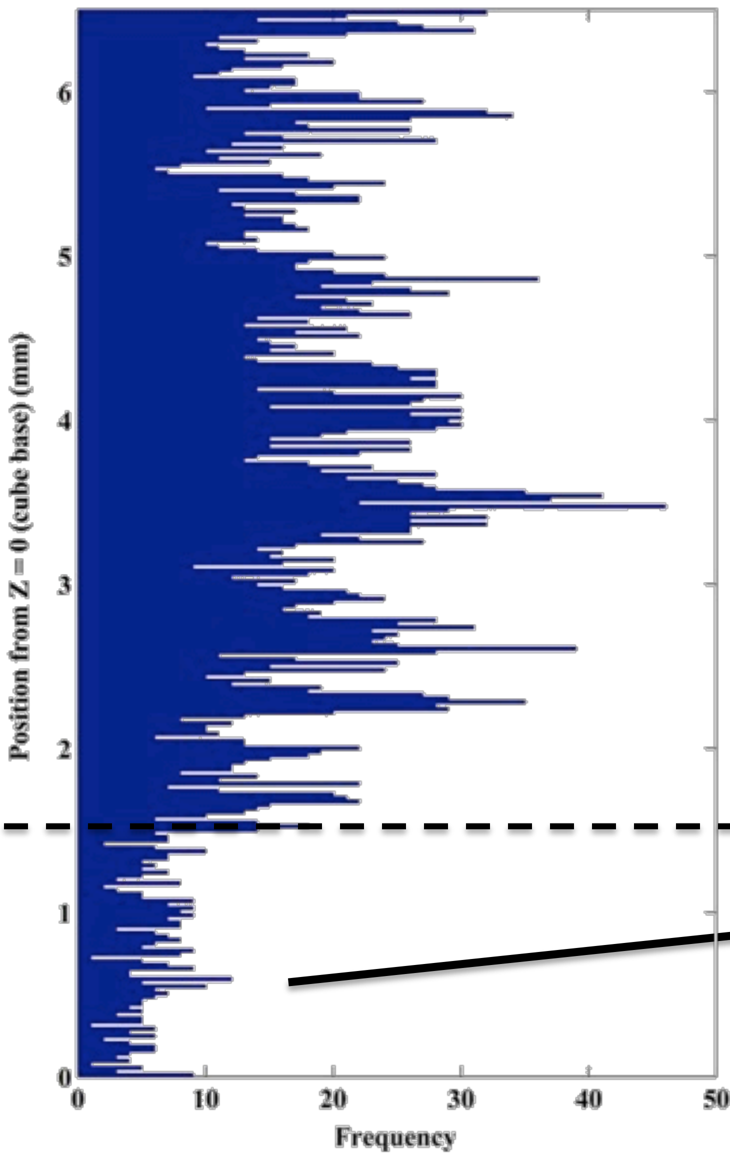

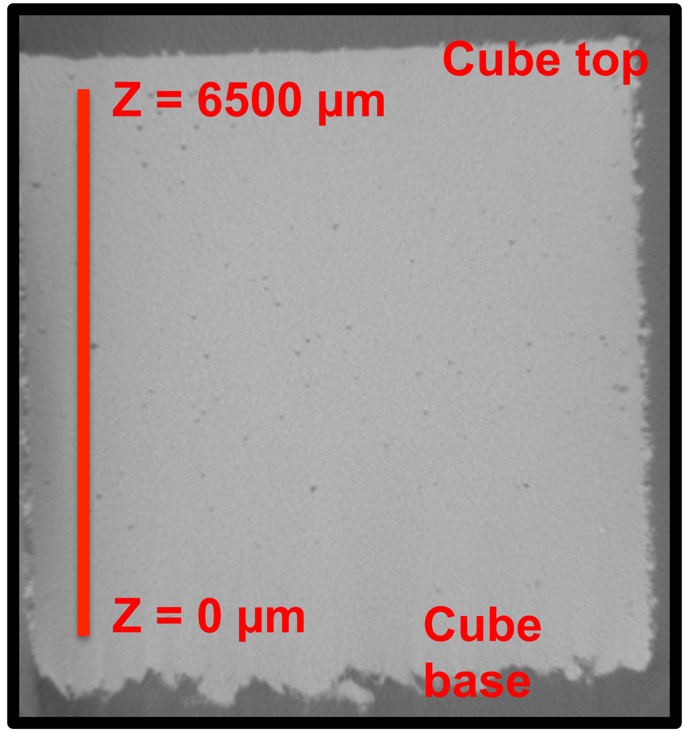

Fewer pores within ~ 1.5 mm of base

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SLM aluminium - material characteristics and enhancement

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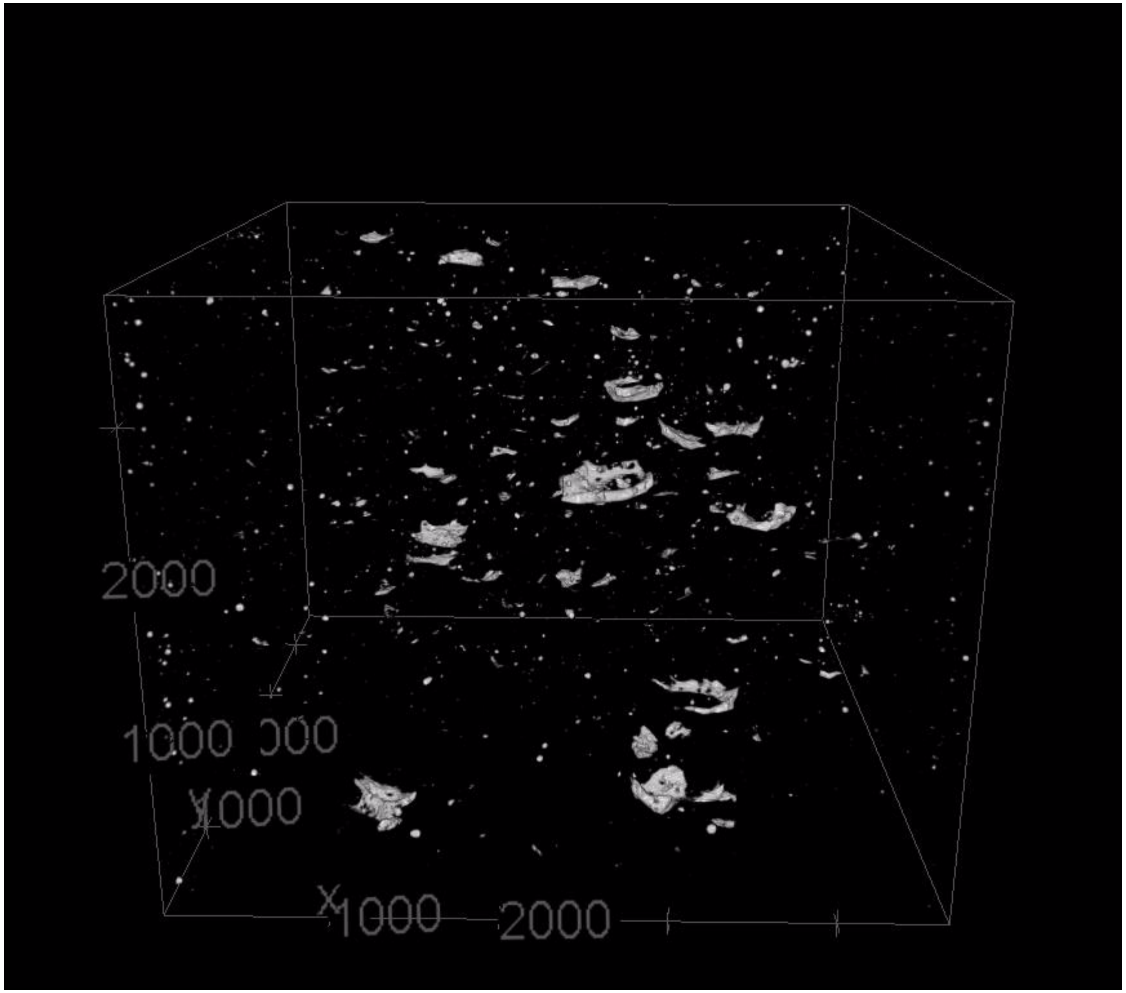
X-ray CT measurements

- accurate porosity
- pore size and shape
- 3D distribution

Implications for:

- part validation
- process development
- failure analysis
- lifecycle modelling



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SLM aluminium - material characteristics and enhancement

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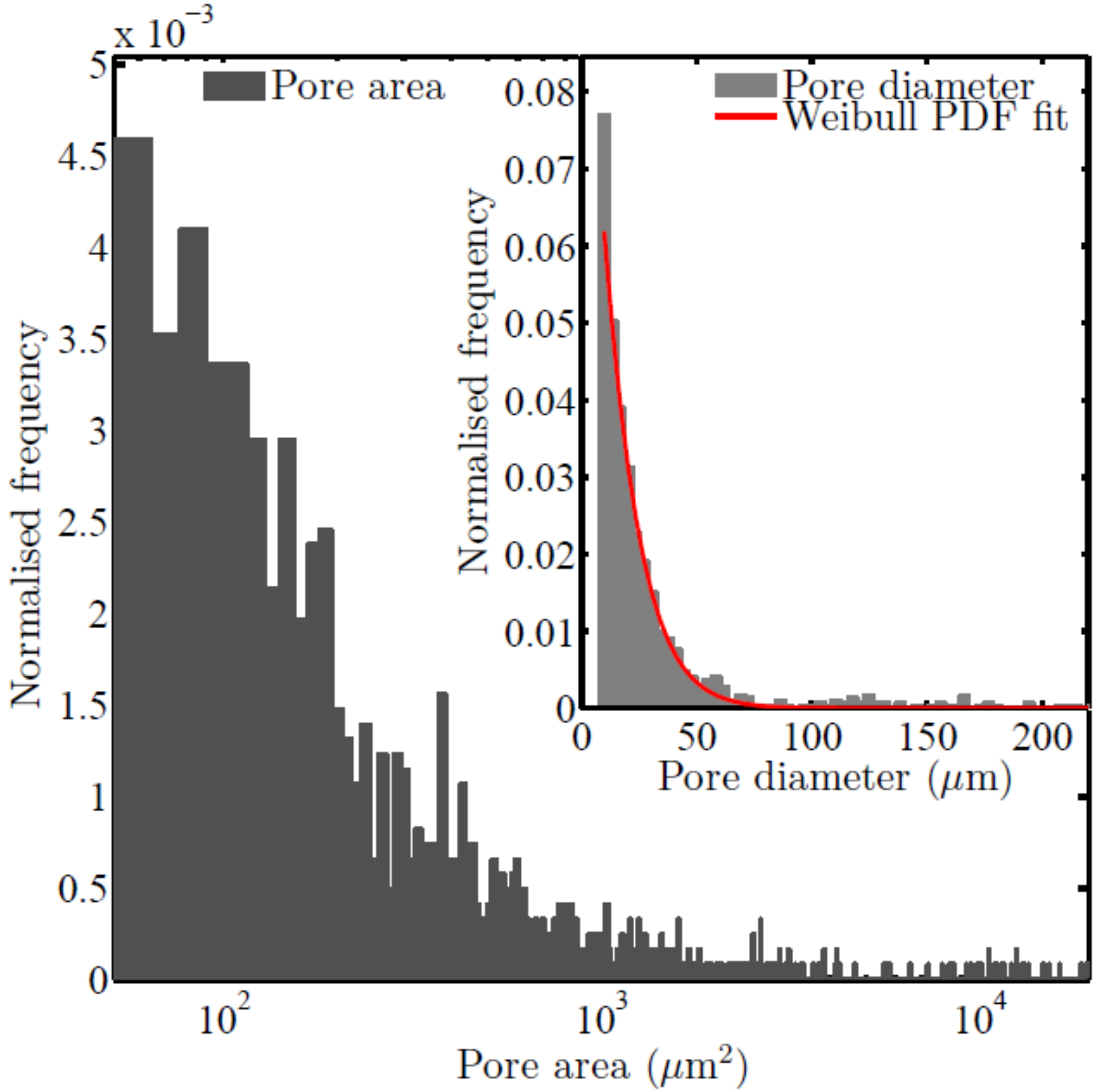
Pore size analysis

Directly related to probability of failure statistics.



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SLM aluminium - material characteristics and enhancement

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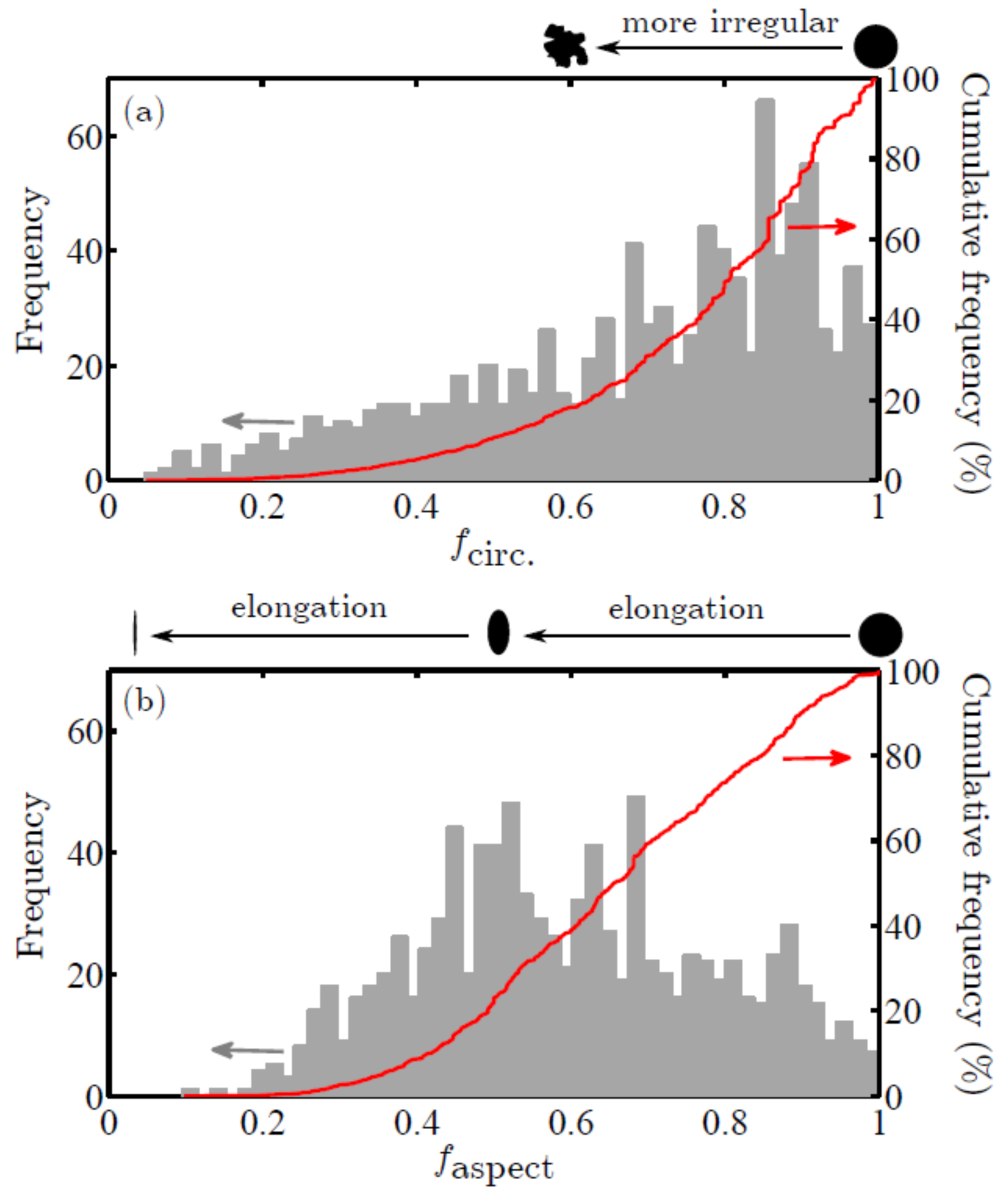
Pore shape analysis

Irregular pores provide stress concentrations and initiate cracks.



Laser Spatter Investigation

Oxidation during SLM

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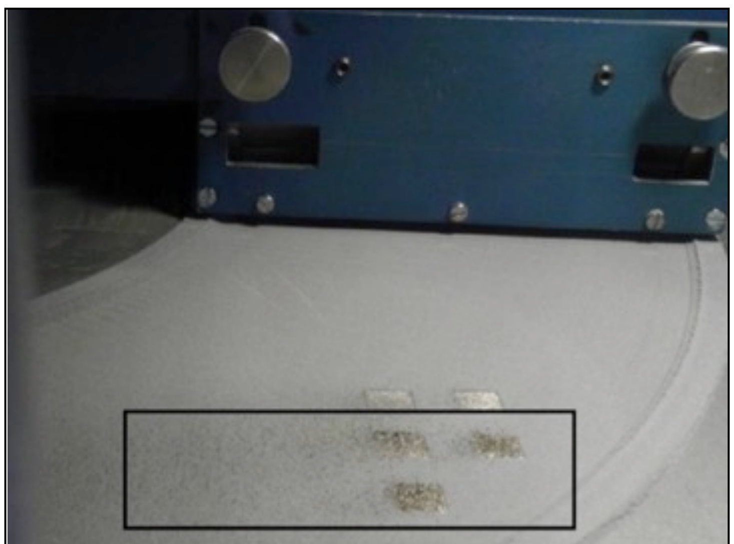
- Broadly speaking the morphology of the melt pools can be controlled adjusting four main process parameters: laser power, laser scan speed, hatch spacing and layer thickness
- As parts are produced in atmosphere with relative high 0_2 partial pressure (hundreds ppm – depending on SLM machine) it is likely that the high temperature reached by the melt pool could trigger the formation of oxides films
- It is generally accepted that oxide films have negligible effect on SLM as long as they are thin enough to be disrupted and stirred in the melt pool by the laser beam
- This might not be the case for all the metal systems that are being processed (different oxide nature for steel, Ti and Al alloys)

Our approach…

- Study the oxidation of different metals during SLM by characterising the laser spatter (and the metallic fumes) that are produced during the process
- Spatter is indeed not affected by successive layer depositions: if oxides are present they should appear in the metallurgical analysis
- Direct comparison of the feedstock material with laser spatter



Laser spatter

Metallic fumes solidification

SLM and materials under investigation

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- Continuous 100W yttrium fibre laser
- λ=1.06 μm and minimum spot size of 20 μm
- Oxygen level 0.2 % (2000 ppm)
- Build platform at 473.15K (200C)
- Materials: 316L, Al-Si10-Mg and Ti-6Al-4V

Processing conditions for the three materials used in this study

		Materials		
		316L stainless steel	**Al-Si10-Mg**	**Ti-6Al-4V**
Layer thickness [μm]		25	40	40
Scan strategy		alternate	alternate	alternate
№ of scans per layer		1	2	2
Laser power [W]	border	37.5	100	40
	inner area	82.5	100	82.5
Laser scan speed [mm/s]	border	250	250	250
	inner area	500	250 and 500*	500

*The inner cross section was scanned at 250 mm/s (first scan) and then 500 mm/s (second scan)

Initial Work - Feedstock material

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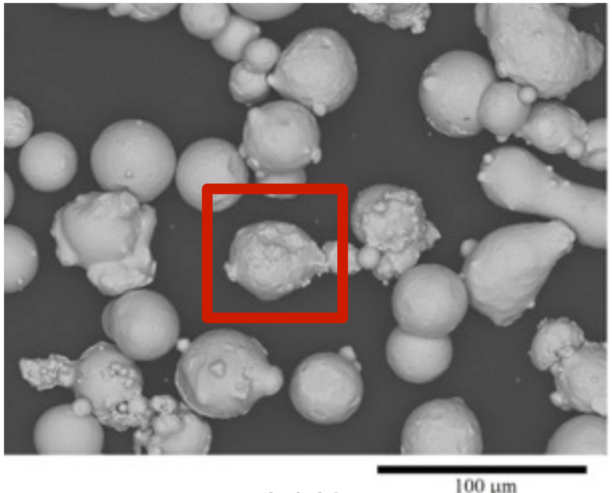
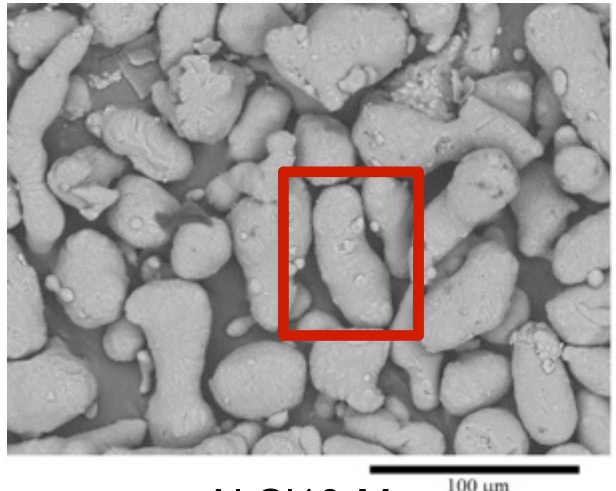
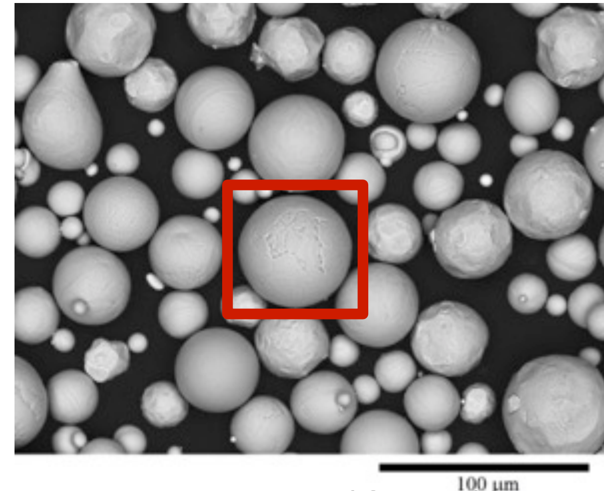


316L



Al-Si10-Mg



Ti-6Al-4V (Gd 23)

Nominal compositions of the pre-alloyed starting materials used in this study

	Fe	Cr	Ni	Mo	Mn	Si	C	P	S	O
316L stainless steel	69.41	16.50	10.10	2.09	1.31	0.52	0.03	0.02	0.01	n/a
	Al	Si	Fe	Mg	Mn	Cu	O			
Al-Si10-Mg	89.26	9.71	0.50	0.41	0.06	0.05	0.25			
	Ti	Al	V	Fe	C	N	O			
Ti-6Al-4V	89.70	6.10	4.10	0.07	0.01	0.01	0.13			

Laser spatter: An overview

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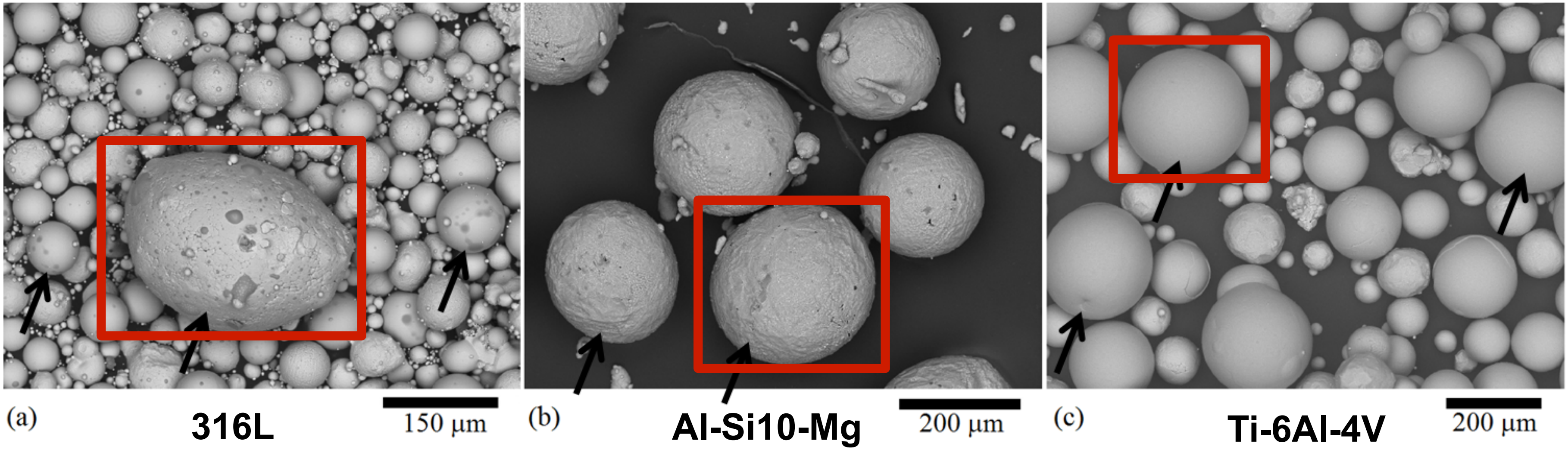
- Laser spatter is typically larger than the initial feedstock (up to ~ 300 μm)
- The spherical shape indicates that molten metal solidifies in flight before impinging on the powder bed
- 316L and Al-Si10-Mg show dark patches suggesting a difference in composition



FIB of Al-Si10-Mg feedstock

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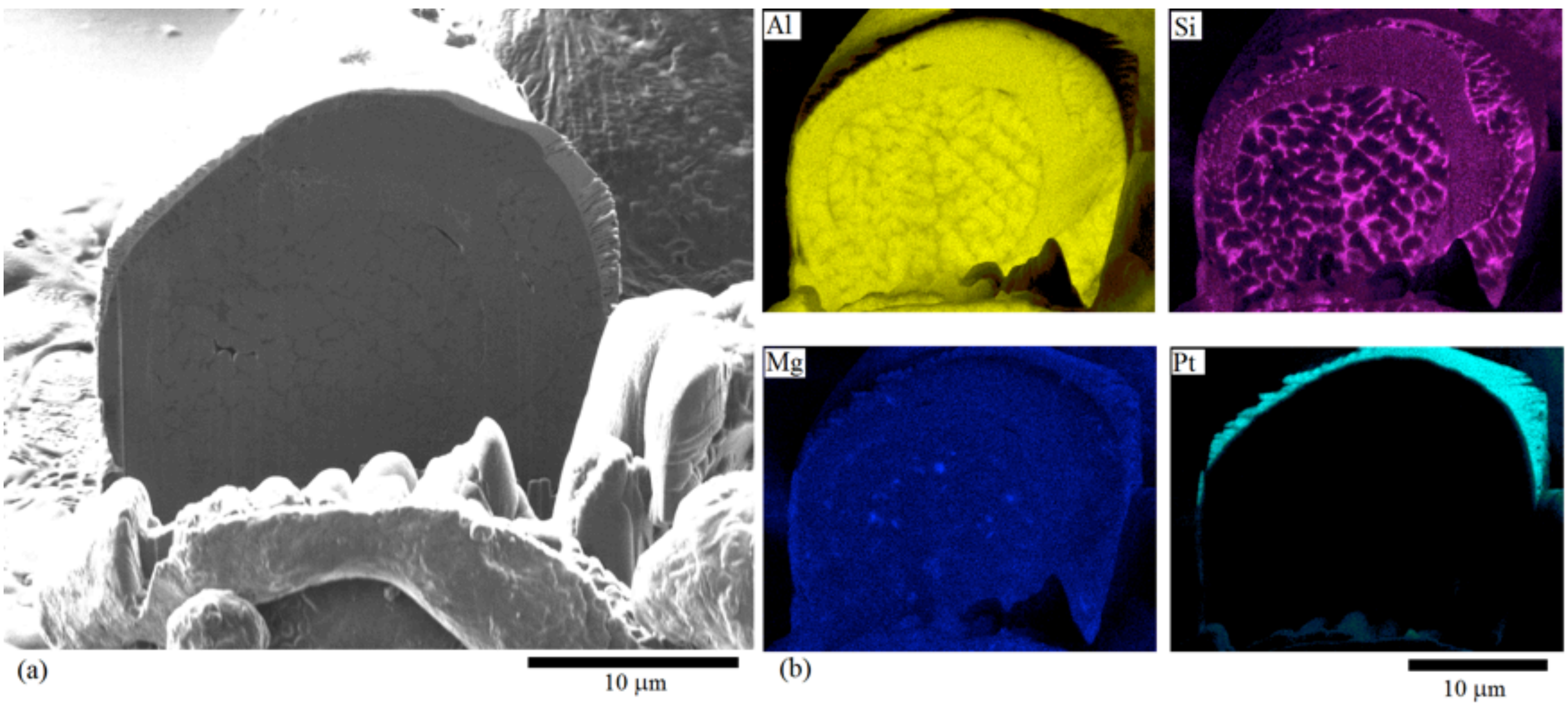
- Core and shell microstructure and extensive cracking
- No intermetellic compounds (Mg_2Si)
- Core: Al grains (α-fcc) surrounded by α+β eutectic matrix where Si-β has a diamond like structure



FIB of Al-Si10-Mg spatter

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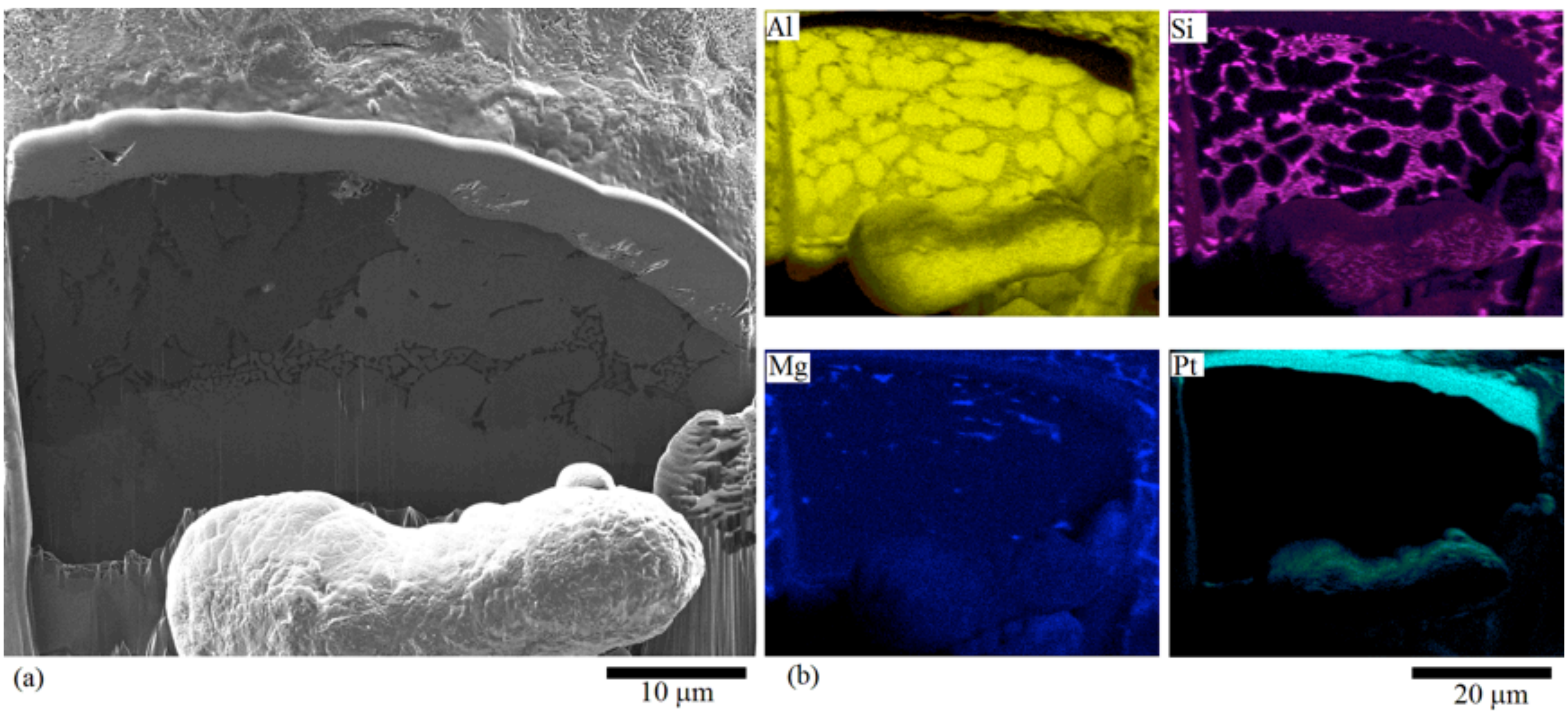
- Homogenous microstructure consisting of dendritic α grains and α+β eutectic matrix
- No oxides in the bulk of the spatter



Oxides on Al-Si10-Mg spatter

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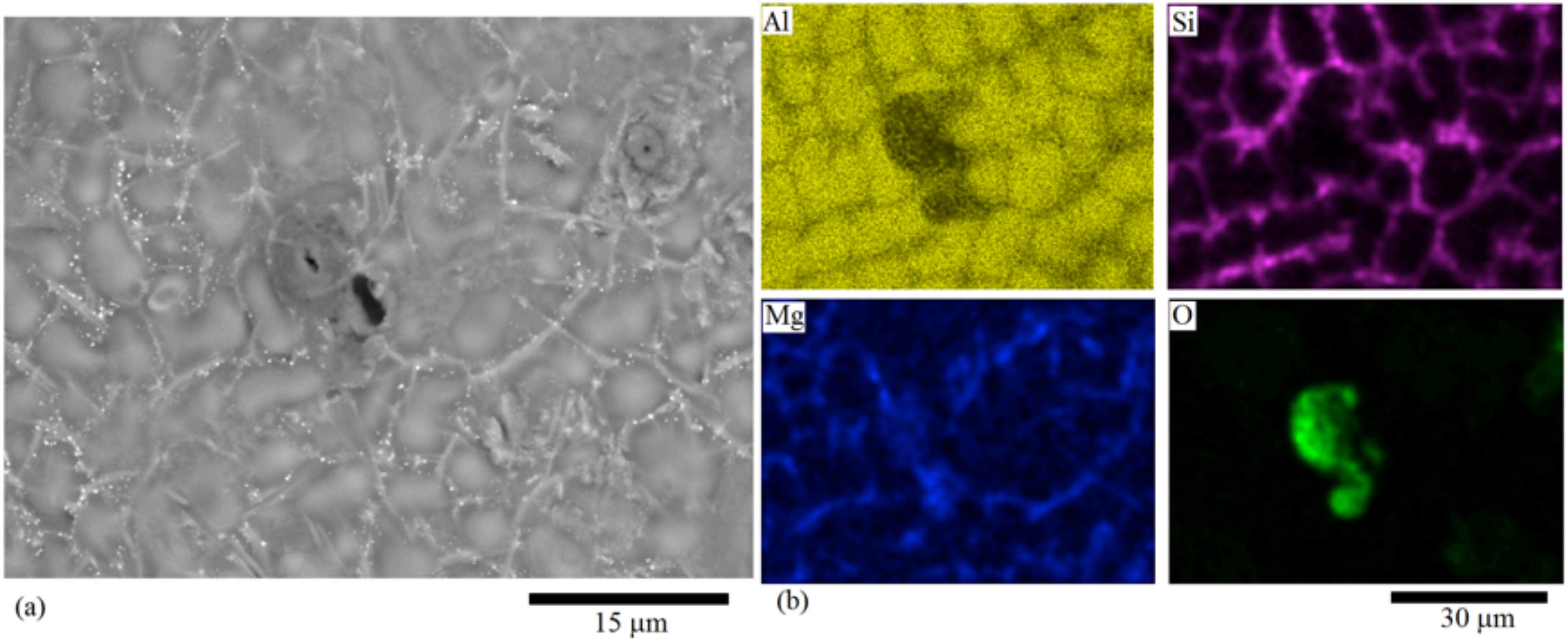
- The surface oxides on the Al-Si10-Mg spatter (dark patches) are mainly Mg - oxides



Oxide formation (1)

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- The oxides films observed only in Al-Si10-Mg are superficial
- This suggests that molten material is ejected as molten metal that then oxidizes – in flight – in the building chamber
- Selective oxidation of alloying elements, predominantly Mg in Al-Si10-Mg, is explained by their higher oxidation potential (O_2 affinity) than the remaining elements (Ellingham diagram)
- Mg oxides grow thicker than Si oxides because the O_2 has limited diffusivity in the latter
- The driving force for the surface segregation of these elements is unclear: clearly not phase partitioning or grain boundary segregation

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Oxide formation (2)

- Surface segregation might be related to the high volatility of Mg; the superheating of the liquid metal would cause diffusion of these elements from the matrix towards to the surface of the alloy
- Alternatively, the apparent surface segregation of these elements might be a result of de-wetting and agglomeration of a surface (molten) oxide formed on the surface of the spatter (no elemental bulk diffusion)

FIB of Ti-6Al-4V feedstock

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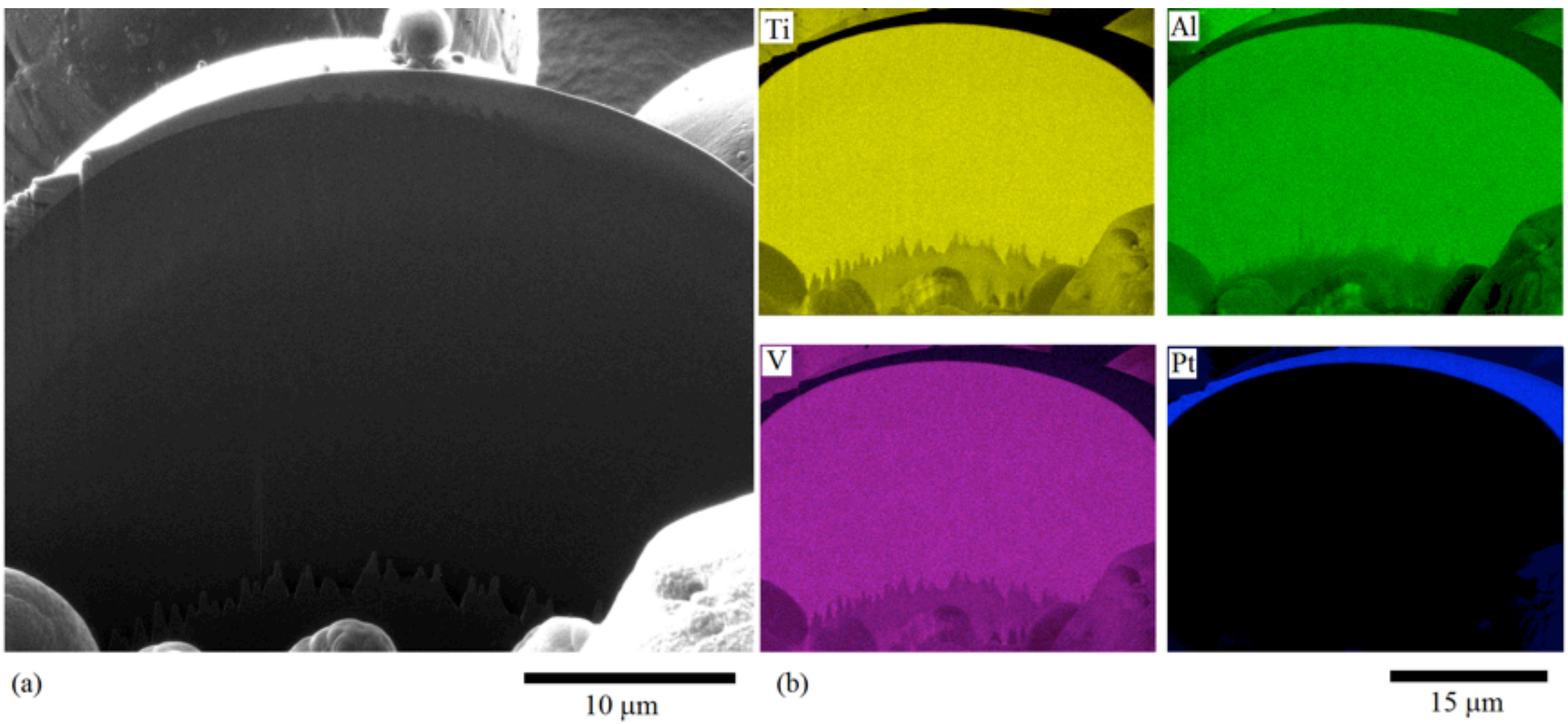
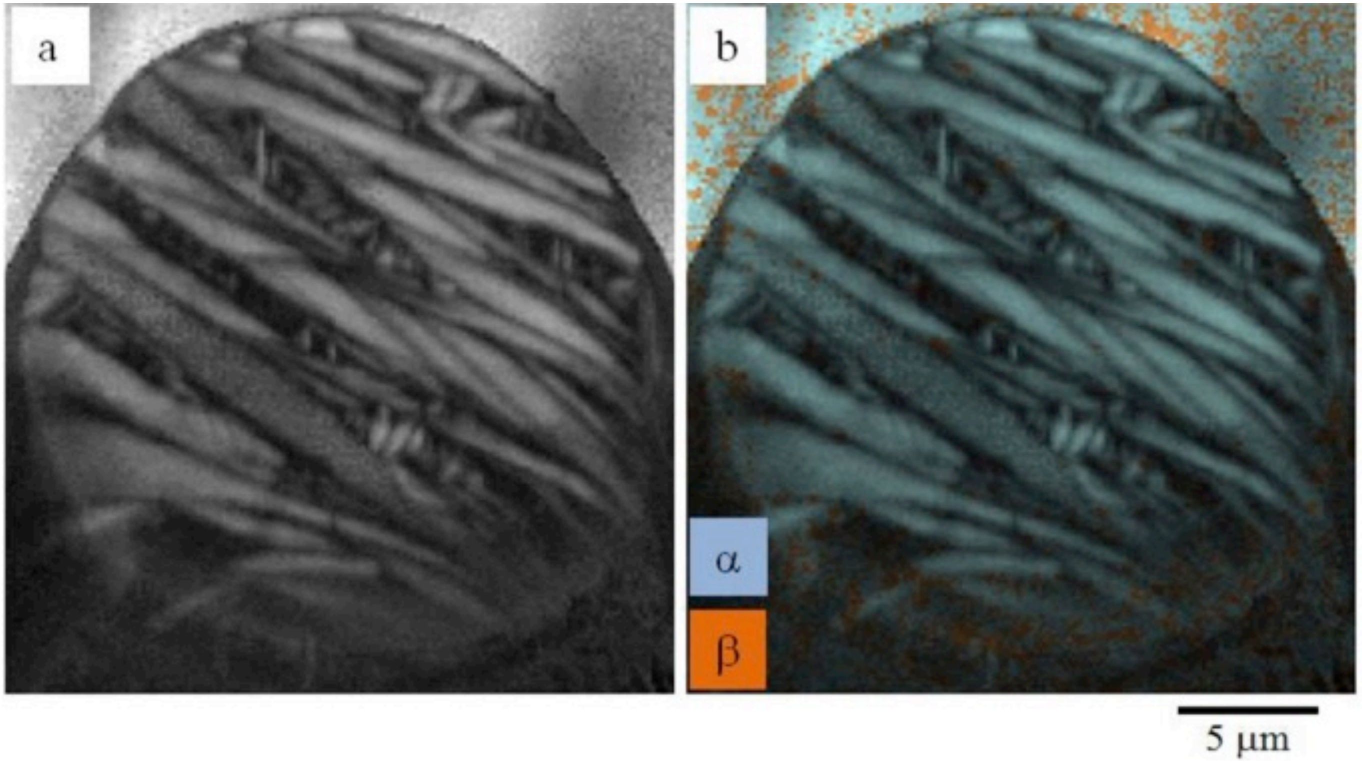
- Grains are not resolved well likely because they are too small to provide ion beam channelling contrast
- All alloying elements are in full solid solution (no precipitates)



FIB of Ti-6Al-4V feedstock

- Microstructure exposed by EBSD analysis
- Feedstock solidifies in single α phase with typical lamellar morphology (no β phase)
- Length and width 16.1±0.3 and 1.9±0.3 μm respectively



FIB of Ti-6Al-4V spatter

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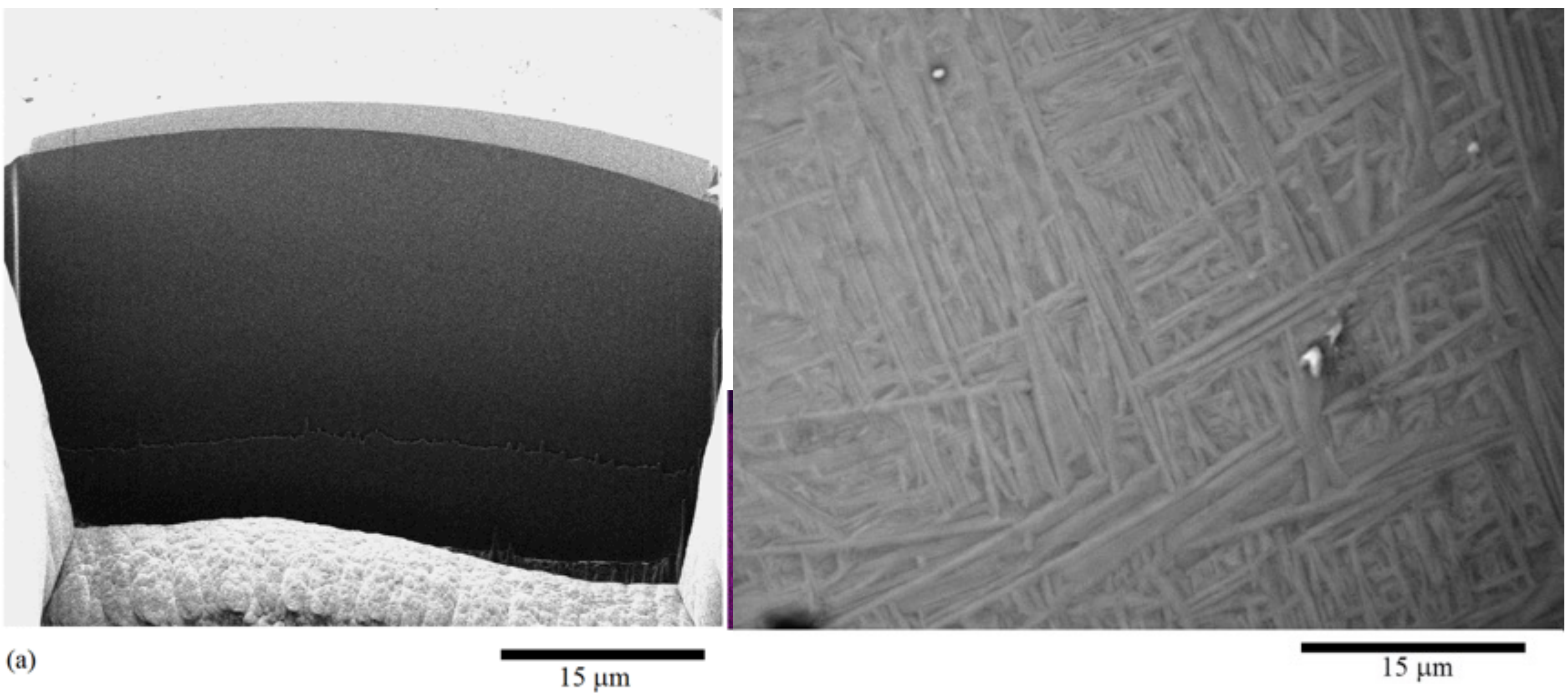
- Alloying elements are in full solid solution
- In contrast to that observed previously, Ti-6Al-4V laser spatter does not display any areas of compositional difference!



A special case: Ti-6Al-4V

- The reduced volatility of the alloying elements in Ti-6Al-4V would explain why no thick oxides are present in the spatter
- It is also noteworthy that unlike Al, Ti can dissolve O_2 up to significant concentrations in its solid phase
- This might explain why, despite O_2 being likely, no stable oxides are present on the surface of the spatter

A special case: Ti-6Al-4V

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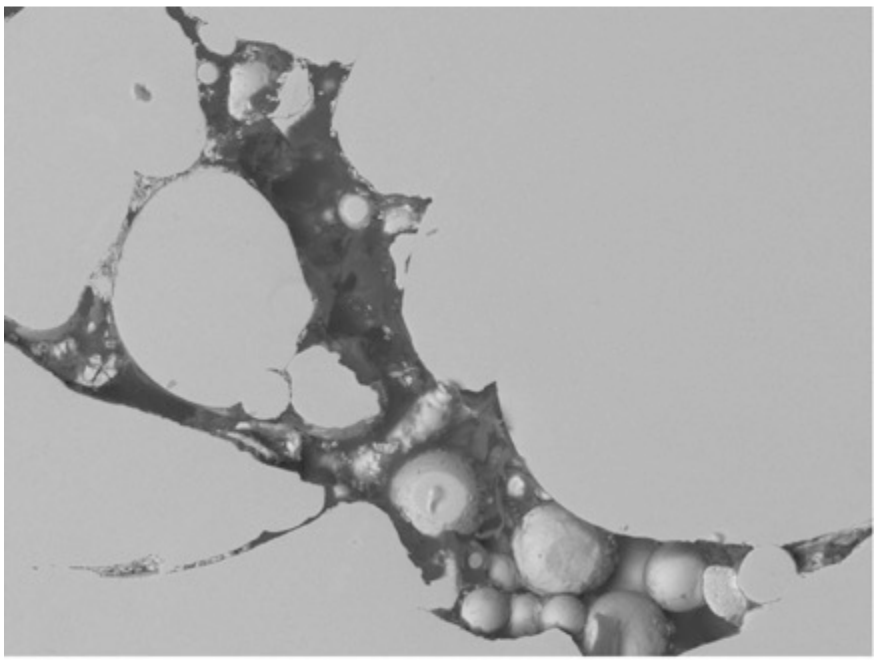
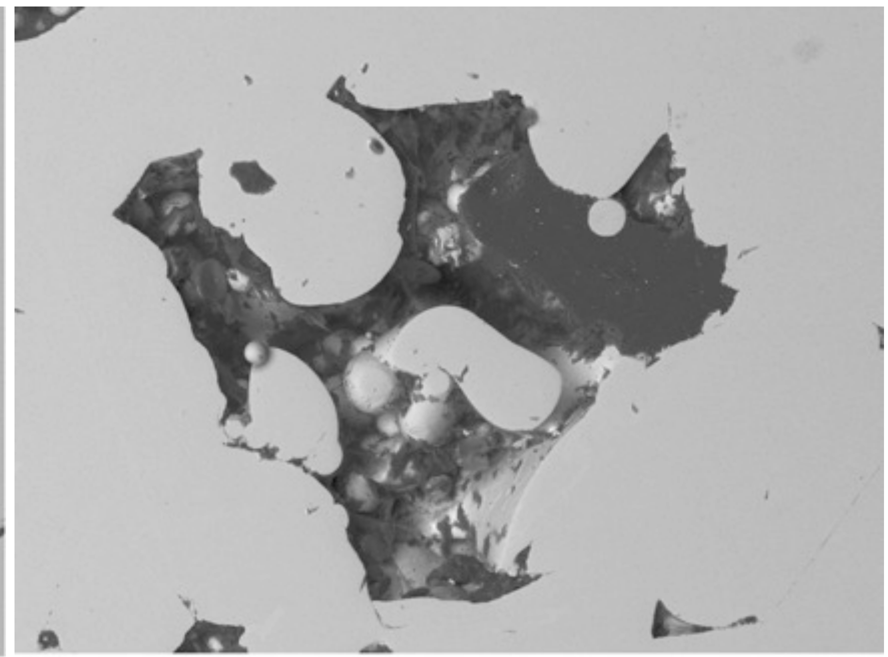
- As in the case of Al-Si10-Mg the spatter is much larger than the feedstock material and thus its contamination on the powder bed might lead to improper powder spreading and lack of fusion



100 µm



150 µm

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Future research

- Scan strategies and laser parameters that would resolve in a less aggressive heating regime and therefore reduce the overheating responsible for spatter generation
- Adoption of a scan strategy where powder bed is initially sintered using low energy density and than re-melted is likely to reduce spatter formation
- Modulation of the shape of the laser pulse, i.e. distributing the laser power density over a longer period of time
- Need to develop materials for SLM that take into account the relative volatility of the alloying elements

Mechanical Properties

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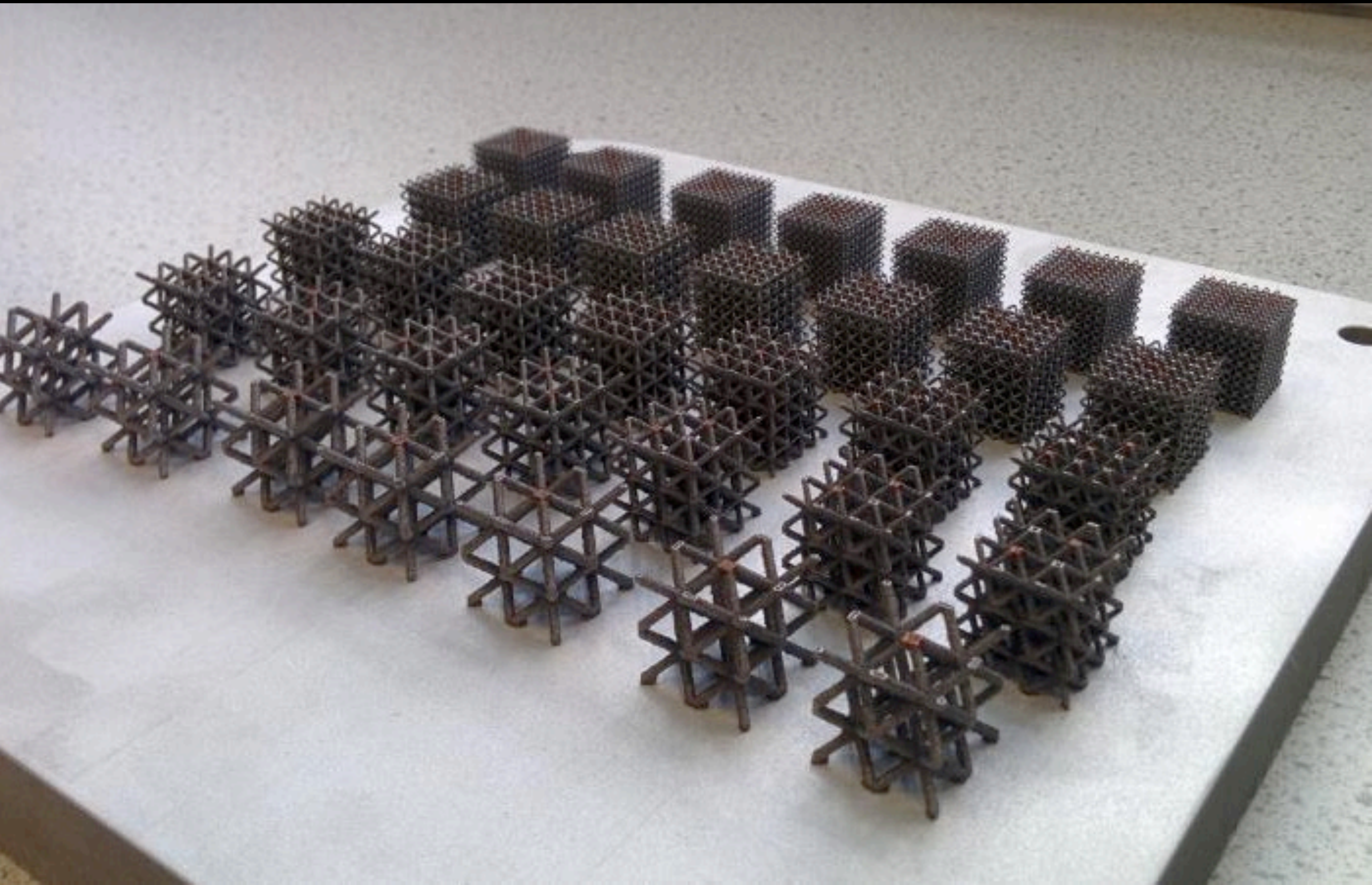

Heat treatment of SLM AlSi10Mg

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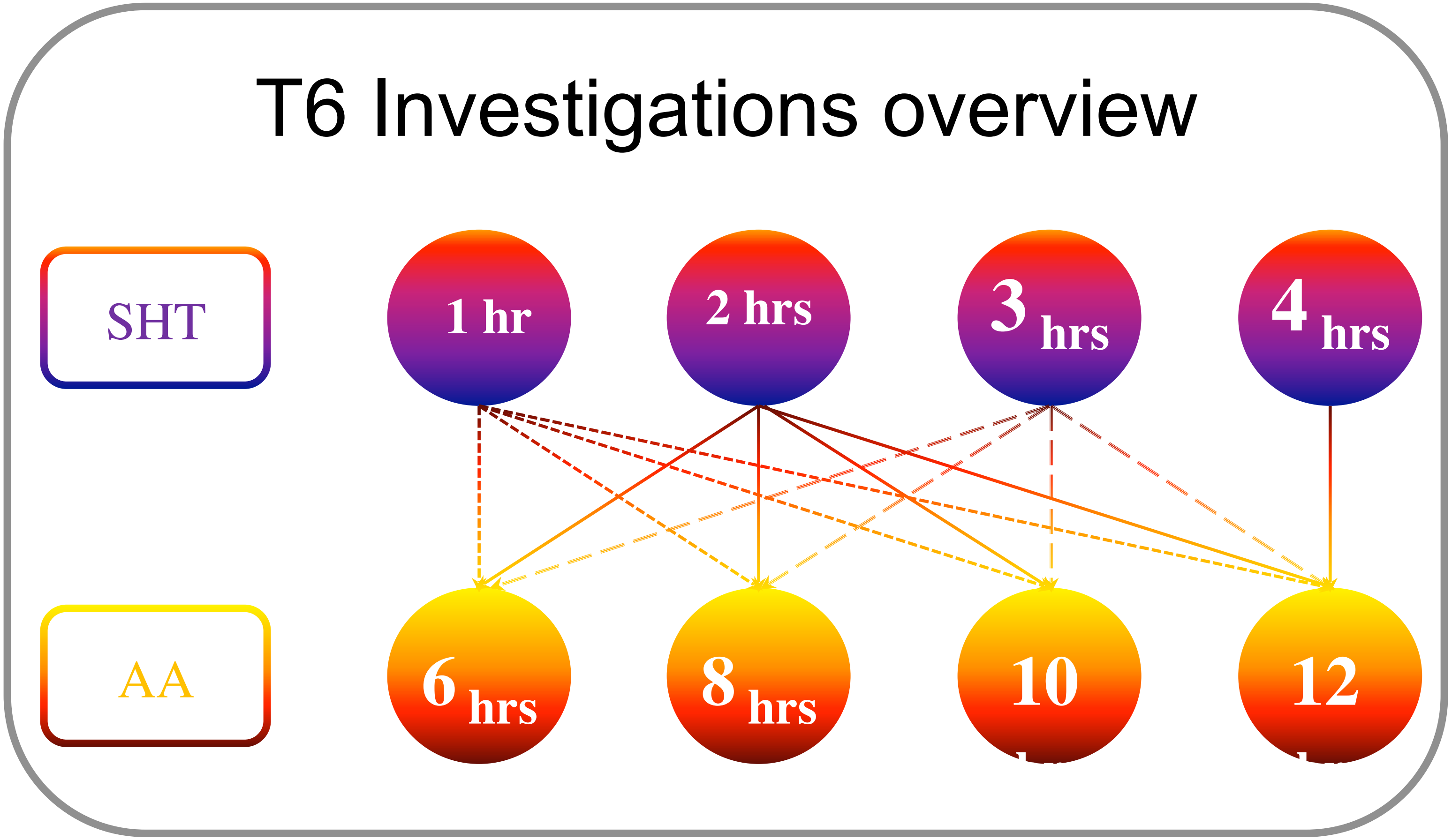
Samples investigated for micro-structure, EDS mapping (ongoing), and hardness (Vickers)



SLM aluminium - material characteristics and enhancement

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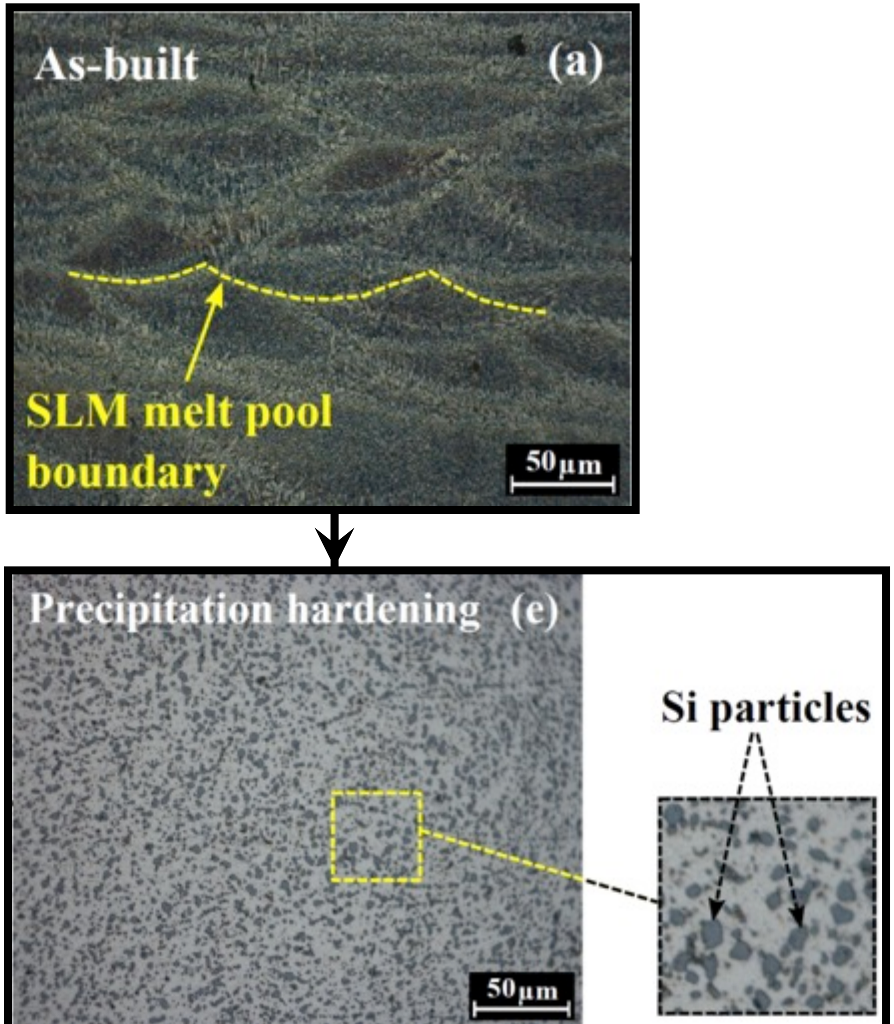
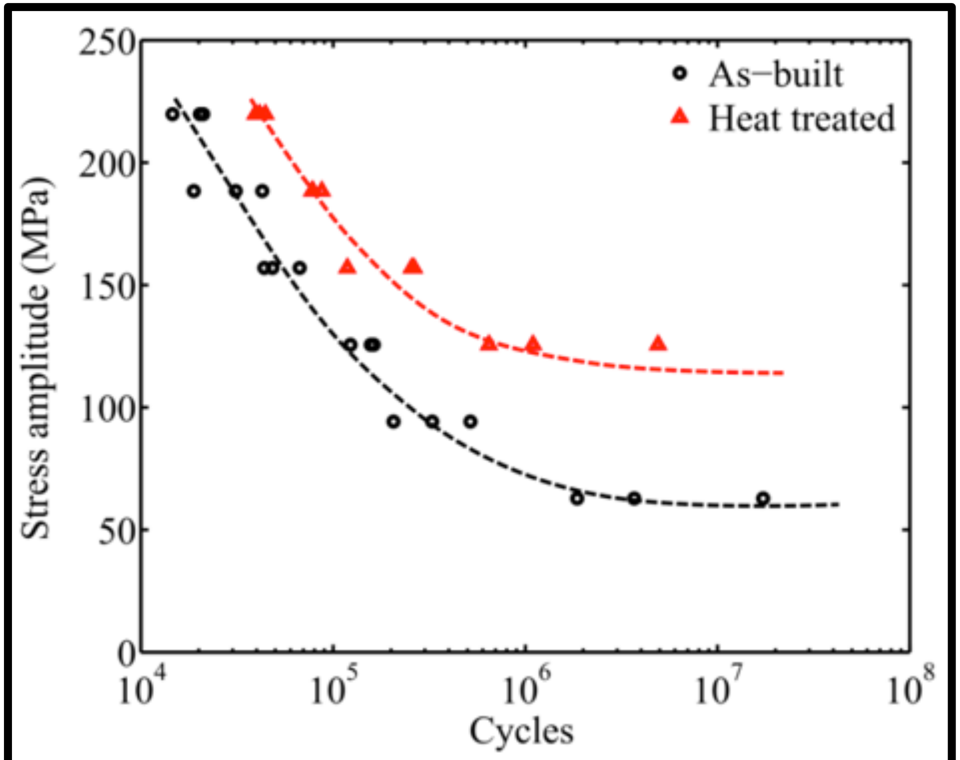
Heat treatment



Results

- microstructure transformation
- enhanced ductility
- enhanced fatigue performance

Fatigue



Fatigue, compression and heat treatment

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- Fatigue S-N curves of SLM AlSi10Mg in 4 conditions;

1	Fabricated			Tested
2	Fabricated	Heat-treated (T6)		Tested
3	Fabricated	Heat-treated (T6)	Machined	Tested
4	Fabricated		Machined	Tested

Fatigue, compression and heat treatment

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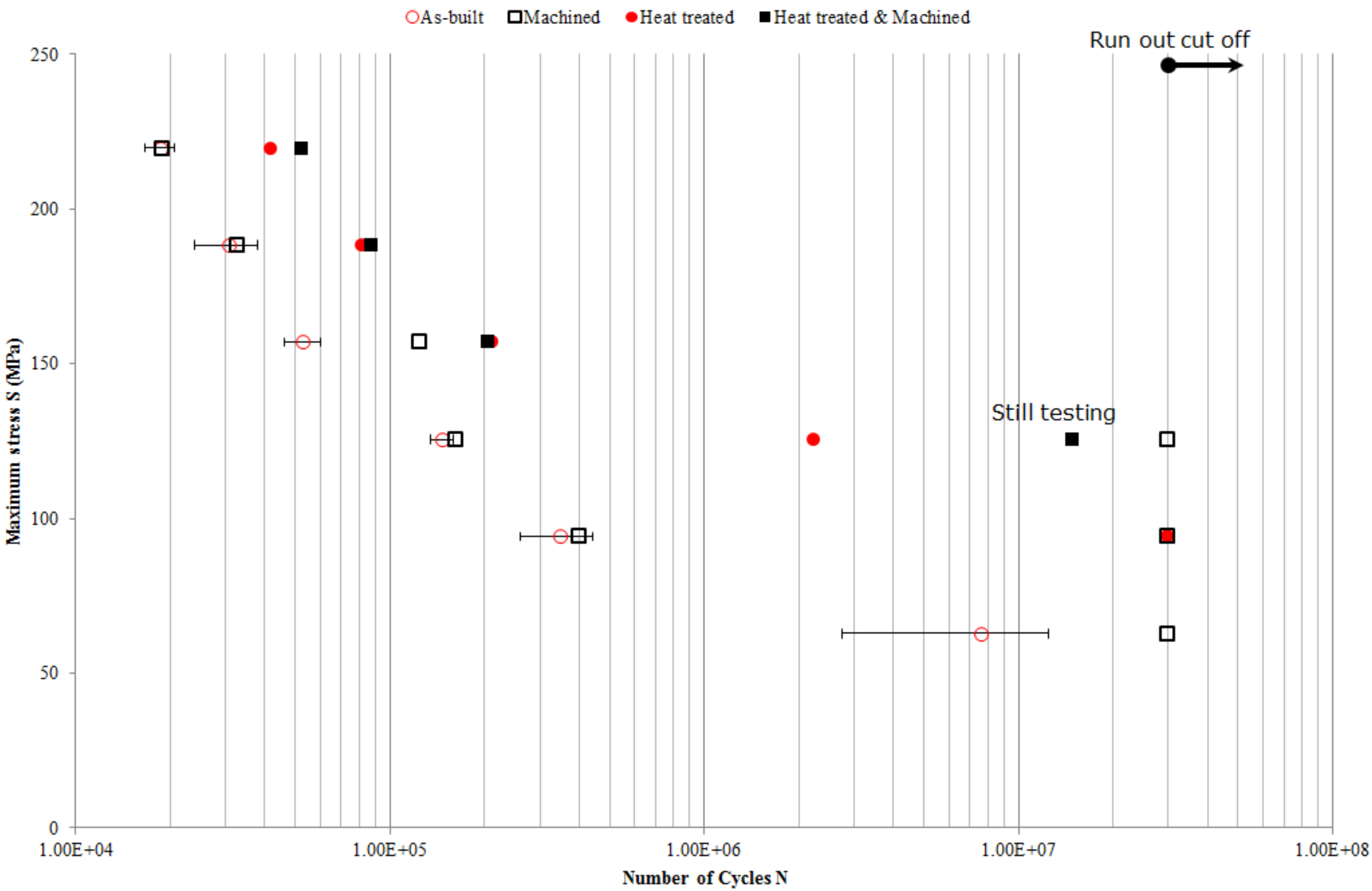

SLM aluminium - material characteristics and enhancement

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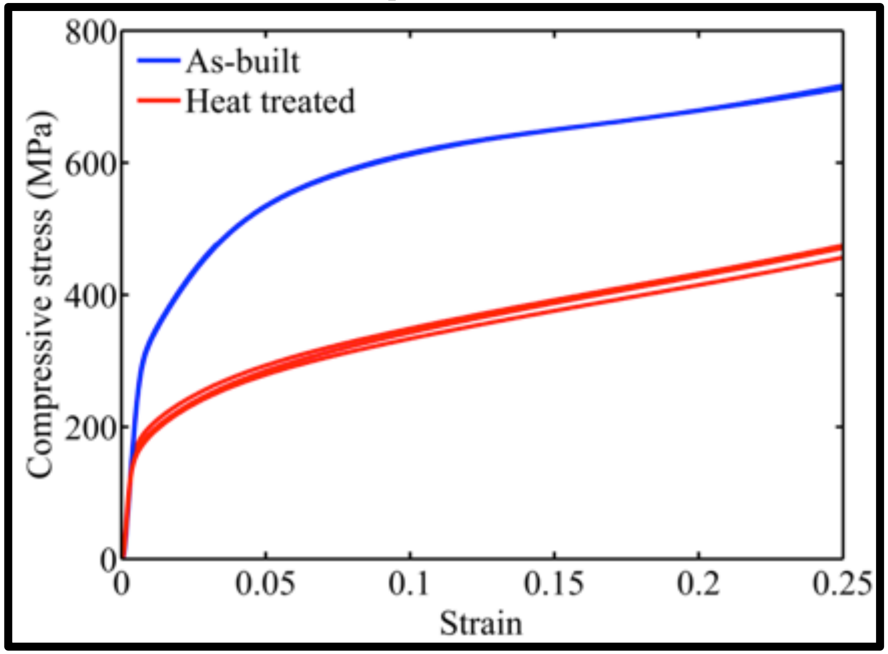
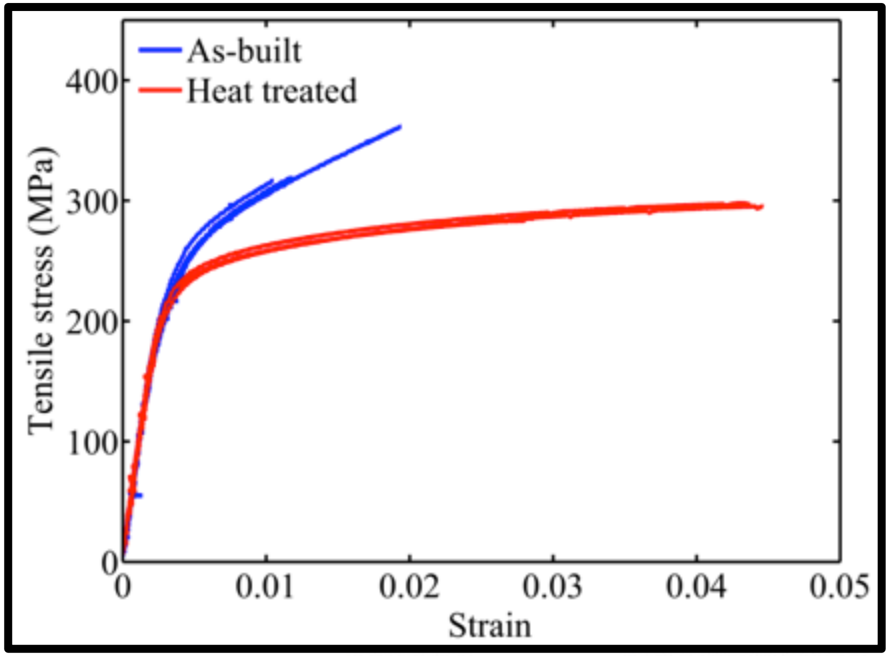
Static mechanical properties of SLM AlSi10Mg

- Elastic modulus – 81 ± 2 GPa (higher than cast A360 ~ 71 GPa)
- Ductility enhanced **threefold** by heat treatment

Compression



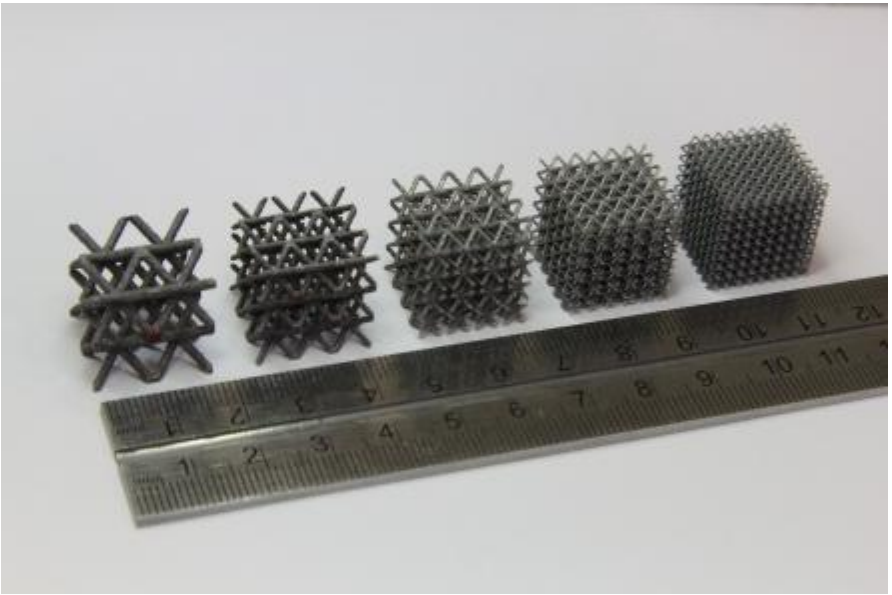
Tension

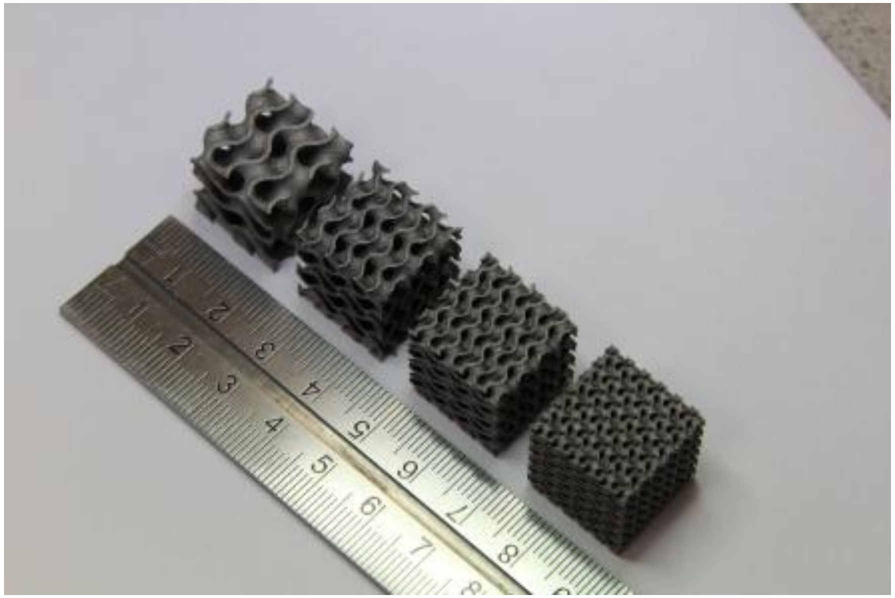


Mechanical properties of latticed parts

Compression.

Comparison of BCC and double-gyroid (DG) lattices





Videos…

BCC and gyroid lattice structures

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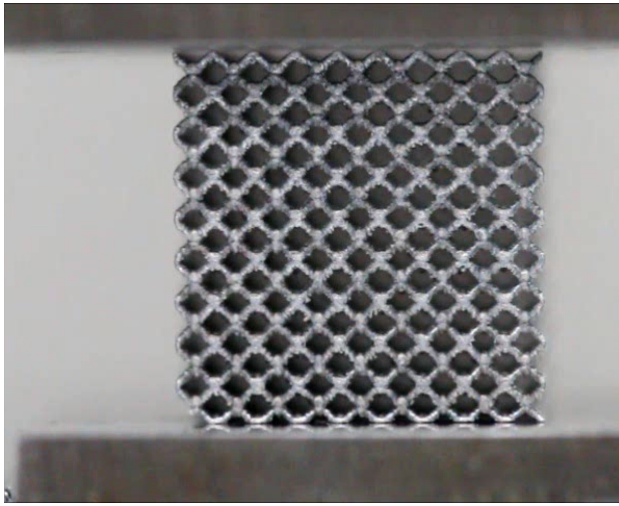
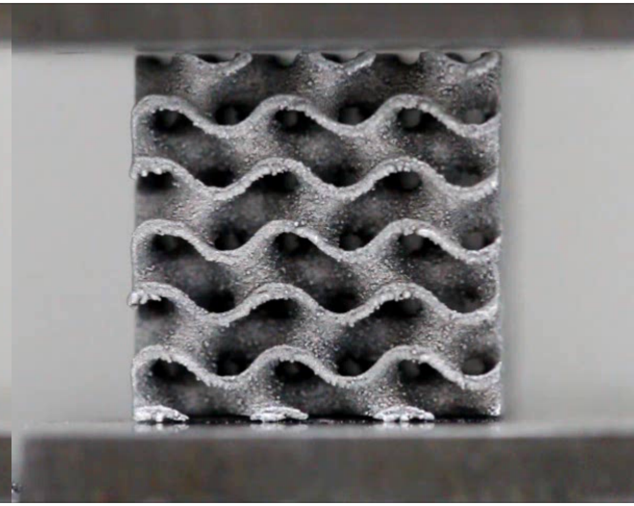
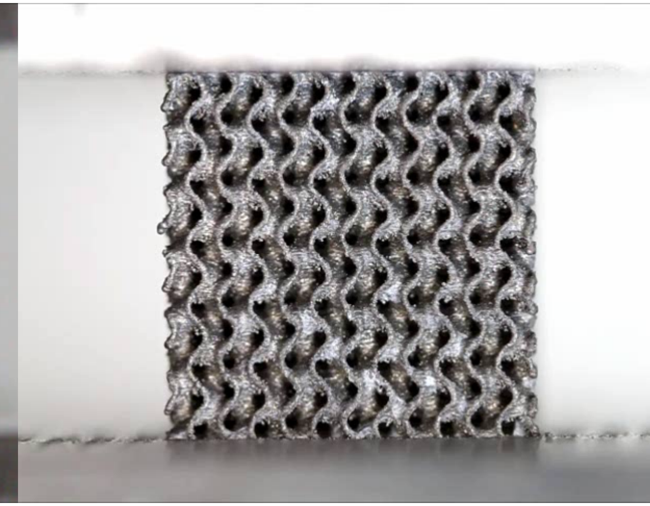


Body-centred-cubic
Al-Si10-Mg
As-built
Diagonal shear
Brittle fracture



Double gyroid
Al-Si10-Mg
As-built
Brittle fracture



Double gyroid
Al-Si10-Mg
Heat treated
Plastic deformation

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Novel lightweight structures

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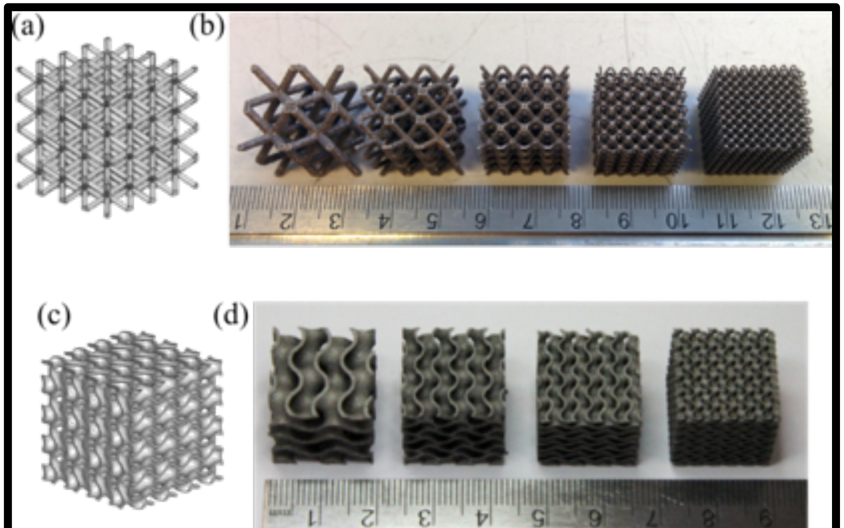
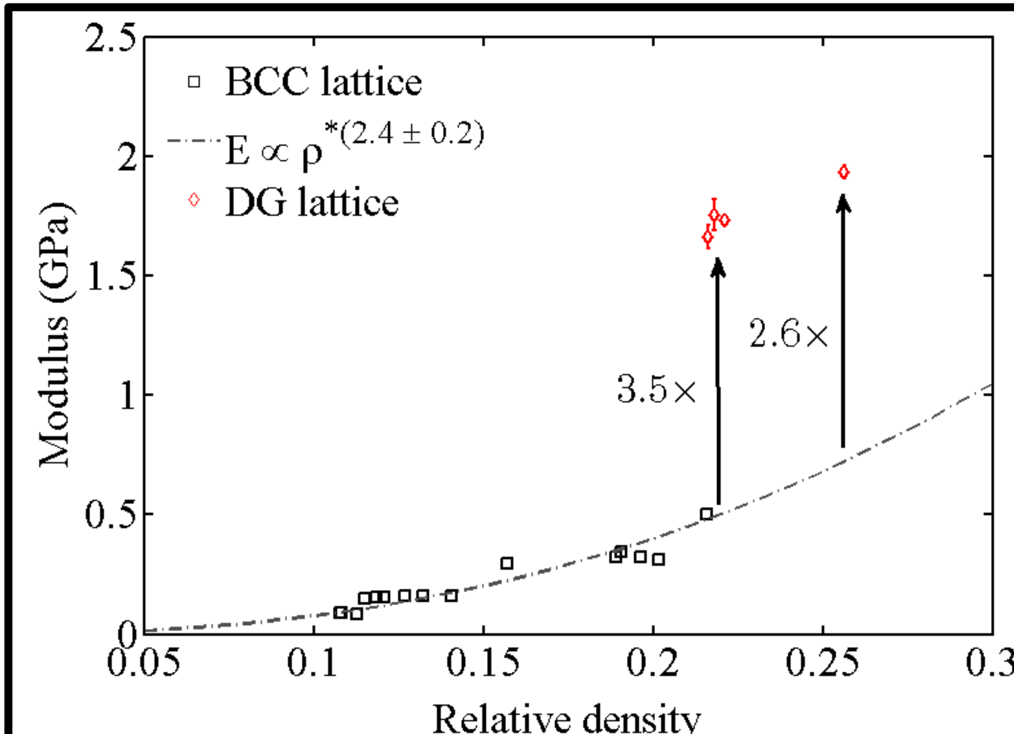
- Double-gyroid lattices out perform BCC lattices – modulus *and* strength
- Heat treatment improves deformation process – eliminates layer collapse





Summary

Those interested in developing SLM to a full manufacturing technology need to take the huge amount of (disparate) research being undertaken in SLM, materials, modelling and development to feed into material and multi-physics models to have intelligence in the process – and to qualify it!

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Many Thanks

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